2018

DEVELOPMENT OF A METHODOLOGY FOR SUSTAINABLE PRODUCT RE-DESIGN FROM PRODUCT ARCHITECTURE PRINCIPLES

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PHD THESIS

UNIVERSIDAD DEL NORTE | Mechanical Engineering PhD Program

UNIVERSIDAD DEL NORTE

DEVELOPMENT OF A METHODOLOGY FOR SUSTAINABLE PRODUCT RE-DESIGN FROM PRODUCT ARCHITECTURE PRINCIPLES

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Submitted to fulfil the requirements for the degree of
Doctor in Mechanical Engineering

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ENGINEERING DIVISION
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2018

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List of Abbreviations

C_1	Number of component variety capable of working in an operational range
C_2	Number of component Variety with more than one functionality
CAD	Computed Aided Design
CE	Circular Economy
CI	Overall Pugh Complexity Index
C_{TM}	Overall Assembly-Disassembly Complexity Index
C_v	Component variety in the product family
DFX	Desing for X
DFMA	Design For Manufacturing and Assembly
ECM	Eco-design Checklist Method
E_i	Recycling Efficiency
EOL	End of Life
FR	Functional Range Index
FV	Functional Variety Index
LCA	Life Cycle Analysis
LFI	Linear Flow Index
MAPs	Modular Architecture Principles
MECO	Materials, Energy, Chemicals, Others
M_R	Total mass of reusable components in the product family
M_T	Total mass of the product family
n	Number of components in the product family
OAP	Open Architecture Products
P	Number of product variants
PF	Product Family
PLA	Polylactid Acid
PV	Product Variant
QFD	Quality Function Deployment
R	Number of reconfigurations in the product family
REI	Recycle Index
RI	Reconfiguration Index
SPD	Sustainable Product Design
V	Mass of virgin feedstock in the product family
WF	Mass of unrecoverable waste generated to produce recycle feedstock
WR	Mass of unrecoverable waste generated in the product family
WU	Mass of unrecoverable waste in the manufacturing of the product family

CHAPTER 1

Structure and Introduction

Contents

1.1 Background

1.1.1 Sustainability

Sustainability is defined from the engineering perspective as the balanced integration of environment, economy and society aspects in any decision making regarding the lifecycle of design products and processes. In this way, sustainability considers all the stakeholders involved in any productive activity, raw material transformation and services. This definition is well aligned with the statement of the concept of sustainable development, which establishes "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Elkington, 1997).

Currently, it is possible to affirm that the future of all species are compromised by the irrational development of human activities. Therefore, sustainability need to be involved in any productive process. Especially, in the field of product development process which faces many engineering challenges not only to fulfil functional requirements but also sustainability critical issues. Several of the most important sustainability challenges are listed below as follows (UN Department of Economic and Social Affairs - Division of Sustainable Development, 2002) (Howarth & Hadfield, 2006):

Environment

- To control and mitigate negative impacts derived from climate change, which affect many productive human activities such as agriculture and increase the risk of illnesses and disease in poorer countries (Howarth & Hadfield, 2006).
- To diminish the resource depletion due to the population growth that involves the increase of exponential increase in the consumption and production of products (UN Department of Economic and Social Affairs - Division of Sustainable Development, 2002).
- To Stop the decline of biodiversity due to the growth of human population, agriculture activities, and pollution (Howarth & Hadfield, 2006).

Economy

- To reverse the extended poverty. At least 30% of the current world's population lives on less than $1.00 USD a day. This situation is mainly happening in third-world countries, especially in regions under armed conflict.
- To break financial influences of individual and companies concerning prices of foods and commodities.

Society

- Need of social policies to face the expected doubling of world population in the next 50 years.
- To sanction human rights violation, especially related to the use of child labor to provide cheap products for the developed countries.
- To diminish discrimination issues for being part of cultural, ethnic or religious groups.

1.1.2 Sustainability in the Product Design process

Nowadays, sustainability and sustainable development are gaining more attention due to the increase of the legal framework associated with company's responsibility and the growing consumer demand for green products (Morbidoni, 2012). It is imperative then, to design more sustainable products to reduce negative impacts such as emissions, material and energy consumption. Regarding product design, sustainability can be highly improved from early design phases, within the designer's decisions are mostly responsible for further sustainability impacts in manufacturing, use and final disposal stages (Ramani, et al., 2010).

It is possible to find approaches in the literature aimed to integrate sustainability into the product development process. Many design methods, checklists, assessment tools and software tools are currently available to measure and integrate sustainability into the lifecycle of products. From the literature review, four main trends are identified concerning methodological efforts to integrate sustainability and the product design process. Such trends are described in detail below:

Design /LifeCycle Design: this trend is comprised of approaches dedicated to including sustainability topics in the product design based on both, qualitative and quantitative knowledge. Eco-design tools such as Life-Cycle Analysis (LCA) based methods, Checklists, Quality Function Deployment (QFD) approaches are included in this category (Fargnoli & Kimura, 2006).

LCA based methods are oriented to analyse the energy and material flow at every stage of the lifecycle of products, considering raw material extraction, manufacturing, transportation, use, maintenance, reuse, recycle and waste management (Curran, 2006). On the other hand, Checklists are qualitative tools widely employed by small and medium companies to assess the environmental impact of any product over its entire lifecycle. Commonly, Checklist provides useful information for assessing particular sustainability topics such energy and material consumptions and toxicity of product versions and alternatives through questions and comparative statements (Luttropp & Lagerstedt, 2006). Finally, methods based on QFD are proposed to include sustainability into the product specification development, considering particular sustainability requirements as customer needs (Choi & Ramani, 2009).

Sustainable Manufacturing: in this category, efforts are oriented to two main aspects. The first is the environmental conscious manufacturing, which considers the process improvement and optimisation, the development of new processes and process planning. The second aspect is the Design for X (DFX) approaches dedicated to improving particular tasks such as manufacturing, assembly and disassembly. Design for Manufacturing and Assembly – DFMA is the most important approach in this field (Ramani, et al., 2010). Although DFMA is focused on minimising production cost and time to market, it is possible to include sustainability considerations associated with environmental benefits in manufacturing and assembly tasks.

Sustainable Supply Chain: research efforts in this category are centred in to optimise and enhance the sustainability performance of all processes involved in the logistics, transportation and integration of components manufactured in different locations. According to Askin and Goldberg (Askin & Goldberg, 2002), supply chain represents a 25% of the total manufacturing cost in the product development process. Concerning sustainability, supply chain approaches are focused on minimising environmental and cost impacts associated with the product development. Besides, several supply chain approaches include the consideration of reusability, recyclability and remanufacturing, which are well-known sustainability strategies.

Sustainable End of life: comprises a field of rapidly growing interest for manufacturers and customers. End of Life (EOL) alternatives provides important sustainability solutions for minimising adverse environmental effects and entailing the opportunity of obtaining profit, giving added value to components and products once the conventional useful time is over. In this approach, three main trends are identified (Ramani, et al., 2010):

Methods for EOL Management: considers the design of products based on the expected EOL strategy (reuse, recycle, remanufacture). EOL management is aimed to analyse the product take-back, recovery and transforming to obtain new components or useful products. This trend implies a high-level knowledge about the product constructive attributes, materials and recyclability.

Methods for Product Design Evaluation: considers the evaluation and comparison of EOL performance for products and components once the useful life is over. Product evaluation provides useful information about which is the most optimal EOL strategy, which entails the maximum recovery potential of the current product design.

Methods for Improving Processes: comprises a set of strategies to facilitate EOL tasks based on the expected EOL considered by the product designer. Particular approaches are included in this trend to achieve a higher EOL efficiency; such methods are: a) Modular Design, oriented to facilitate the component sharing to provide common characteristics among products and product families. b) Part Standardization, focused on facilitating disassembly tasks and components handling contributing to the economies of scale in the recovery operations and the interchangeability of components. c) Take-back management, dedicated to analysing the quality, quantity and timing of EOL in products. d) Design for Disassembly, oriented to facilitate the product disaggregation to provide reuse, remanufacturing and recycling tasks. e) Design for Reuse and Remanufacturing, based on the design for rapid and easy repair, testing, cleaning, inspection, refurbishing, replacement, and upgrading of product components. f) Design for Material Recovery, based on the robust selection of manufacturing materials, mainly to guarantee the maximum possible material recovery for reprocessing when the product's useful life is over.

Despite the four main design approaches for sustainability previously mentioned, Sustainable Product Design – SPD comprises many more aspects and topics such as social and economic effects from the product lifecycle process on society, environment, and customers among others. Due to the complexity of SPD, holistic approaches can be tedious and impractical. To visualise such complexity, Jawahir et al. (Jawahir, et al., 2007) summarise one of a complete holistic consideration of all aspects associated with SPD through six main categories: Functionality, Manufacturability, Resource

Optimization and Economy, Environmental Impact, EOL Optimization and Societal Impact. Figure 1 shows the main aspects required to develop SPD processes.

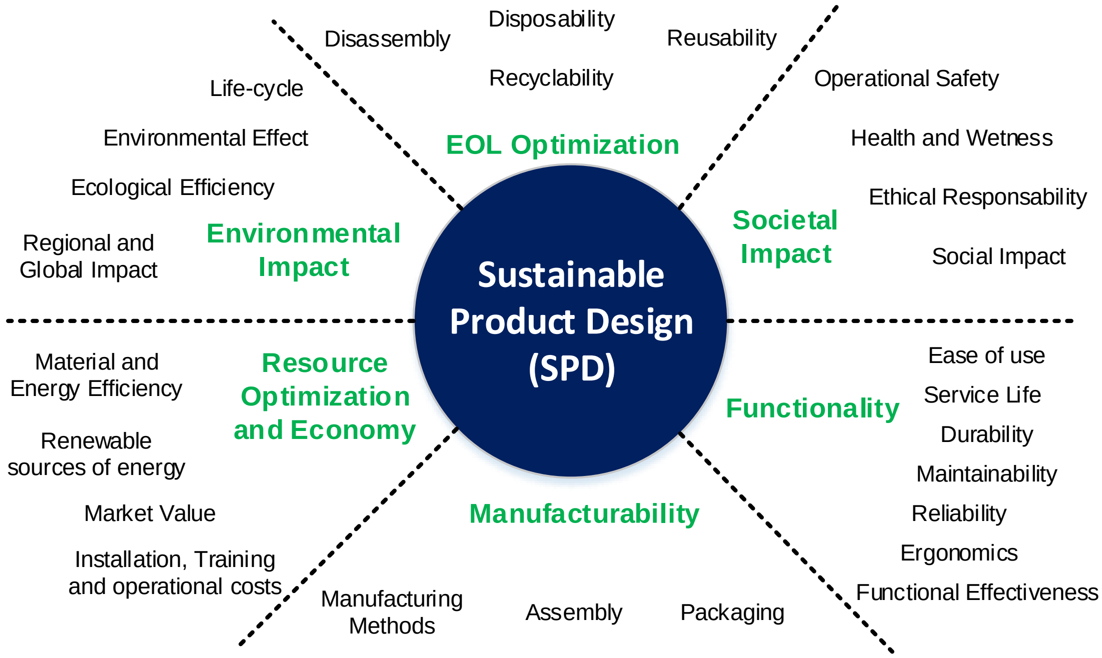

Figure 1: Topics related to Sustainable Product Design. Based on Jawahir et al 2007.

As is showed in Figure 1 , SPD is a highly complex topic based on multiple criteria. Therefore, the analysis of sustainability can be performed from many different perspectives and from particular lifecycle stages, stakeholders among others. Hence, the main challenge for designers should be oriented to both maximise functional attributes and minimise adverse impacts from the product lifecycle. Such main challenge can be appropriately analysed from early design stages, where the sustainability impacts and functional attributes can be defined and weighted according to the stakeholder's interests. According to Ramani et al. (Ramani, et al., 2010) and Ma & Okudan (Ma & Okudan, 2016), the following particular goals required to be covered from the product design process to achieve the proposed main challenge:

- To reduce materials and energy consumption associated with manufacture and lifecycle of products.
- To reduce toxic emissions from product degradation during its lifecycle.
- To maximise the number of recyclable materials and renewable resources in the product development process.
- To increase the efficiency of products during its lifecycle.
- To provide personalised functionalities and attributes in the design of new products.

1.2 Need for researching in Sustainable Product Design

According to the state of the art, sustainability and market trends, the following aspects are listed as main reasons to dedicate research efforts in the SPD field:

- The overall sustainability of products is just achieved from early design stages, which offer the highest impact on sustainability (Ramani, et al., 2010). Sustainability attributes in further stages such as manufacture, use and EOL are largely fixed once the product design is settled.

- Sustainability issues and current market trends require of integration approaches to ensure a robust product design process that considers not only functional attributes for mass individualisation but also friendly lifecycles capable of entailing a circular economy model based on recycling, remanufacturing and reuse tasks.

- The increasing of standards and regulations concerning sustainability in manufacturing companies should be adequately addressed from their design departments to ensure both, high competitiveness and added value based on the sustainable behaviour of customers.

1.3 Research Objectives and Research Questions

1.3.1 Research Objectives

General Objective:

The overall main goal of this project is: To develop a product design methodology from the integration modular architecture principles and circular economy to generate more sustainable product families.

Specific Objectives

1 To characterise the modular architecture principles from the sustainability perspective and its impacts during manufacturing and use after reviewing state of the art concerning design for sustainability methods and trends.

2 To formulate a design method centred on sustainability taking into account modularity, circular economy strategies and the development of particular sustainability indicators.

3 To validate the proposed methodological contributions through its application on a product family case study.

1.3.2 Research Questions

- *How can modular architecture principles be used to increase product sustainability performance?*
- *How can products designed through open architecture be integrated into the circular economy model?*

1.4 Structure of this thesis

This PhD thesis has been structure in seven main sections described as follows:

Chapter 2: Literature Review

This chapter includes a background review regarding SPD, focused on the lifecycle of products. Additionally, it reviews manufacturing paradigms and market trends, especially the mass individualization paradigm and Open Architecture Products. Finally, the circular economy concept, key strategies and attributes among others are reviewed since they are fundamental topics for this project. This chapter summarises state of the art and the research opportunities concerning topics aforementioned.

Chapter 3: Modularity Strategies for Sustainability

This chapter describes the most important topics related to modularity and Modular Architecture Principles - MAPs.. A sustainability characterisation of MAPs and design challenges identified during the implementation and design of open architecture products.

Chapter 4: Methodological Contributions

This chapter comprises ten methodological contributions proposed into the traditional four-phase design method to design sustainable open architecture products based on MAPs. Methodological contributions are described as design task into the Need Clarification, Conceptual Design and Basic Design stages. A set of sustainability indicators is proposed to compare and assess the influence of the methodological contributions in the design of the case study.

Chapter 5: Case Study: Re-design of a family of prosthetic hand devices for children

Chapter 5 consists of the implementation of the methodological contributions proposed in Chapter 4 through a product family of prosthetic hand devices for children. Each design task is developed systematically through the design phases demonstrating the information flow and design activities developed.

Chapter 6: Results and Discussion

This chapter summarises a description of results obtained from the implementation of the methodological contributions on the case study. A discussion regarding the changes in the set of sustainability indicators is also developed.

Chapter 7: General Conclusions and Future Works

Conclusions from the proposed approach, its implementation and results are summarised in this chapter. Also, future works concerning the limitations of the methodological contributions are described as well.

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Chapter 2

Literature Review

Highlights

- The state of the art regarding product design for sustainability is presented.
- Trends about Mass customization, Open Architecture Products and Circular Economy are summarized.
- Relevant research opportunities about product design for sustainability are presented.

Contents

2.1 Introduction

Nowadays, sustainability is considered a highly recommended and in many cases mandatory issue in any product development process. The increasing of legal, market and financial pressures on manufacturing industries to develop sustainable products pushes towards the obligatory consideration of sustainability requirements and the use of design tools and strategies aimed to reduce the negative environmental, economic and social impacts during the development process of product families. On the other hand, the mass individualisation is consolidated as the dominant product-manufacturing paradigm involving high personalization, which entails more complex product design processes, and the increase of resource depletion due to the population growth and the number of possible market segments.

From a technical perspective, the use of Open Architecture Products (OAP) is proposed as a solution to face the functional requirements involved in the mass individualisation paradigm by the use of modular based platforms. However, its implementation does not contemplate the sustainability aspect. This is commonly analysed using Life Cycle Assessment (LCA) tools or eco-design approaches. In addition to conventional LCA and eco-design approaches, the Circular Economy (CE) model enables a robust and promissory framework to face both, mass individualisation and sustainability requirements. This model includes strategies to a) facilitate the supply chain among manufacturing, use, and End of Life (EOL) phases, b) extend useful life of products, and c) improve the use of resources through its adaptability to uncertain and changing customer requirements

This chapter introduces and analyses state of the art regarding the concepts of Sustainable Product Design , Product Manufacturing Paradigms, OAP and CE. Trends, perspectives and research opportunities identified from the analysis of concepts above are described as well. The chapter also provides the readers with the knowledge required to understand the integration of sustainability within the product and the development process of product families.

2.2 Sustainable Product Design (SPD)

Sustainable Product Design (SPD) can be defined as the integration of sustainability attributes within the product design process. Therefore this process should a) integrate environmental, economic and social dimensions, and b) contribute to the transition towards a more sustainable society (Schöggl, et al., 2017). From the perspective of product development, the environmental dimension is commonly associated with energy and material consumptions, and emissions and waste generated. Regarding economic dimension, SPD is related to cost incurred (including workforce, raw material, manufacturing equipment among others) and profits. Lastly, social dimension is commonly studied from the perspective of negative effects derived from emissions over health and safety of worker, and community and customer wellbeing.

2.2.1 SPD in Life-Cycle of Products

According to the literature analysis, it is possible to identify four design categories along the lifecycle of any product, which are widely employed in industry and academic fields. These categories are:

Design for Life-cycle: related to the design of products based on its sustainability impacts during the whole product lifecycle. Most of the existing approaches in the literature are associated with LCA, which provide useful information about the expected impacts regarding emissions and consumptions depending on the manufacturing materials and its management during all lifecycle stages. Methods based on LCA are considered the most objective tools to assess the environmental profile of any product or process (Curran, 2006).

Design for Sustainable Manufacturing: this category comprises the tools and methods aimed to reduce the negative impacts during the manufacture, which is considered the main stage in the lifecycle that consumes resources directly and generates pollution (Gutowski, 2004). The main approaches included in this category are related to a) improvement and optimisation of processes, b) development of new cleaner manufacturing processes, and c) process planning (Ramani, et al., 2010).

Design for Sustainable Supply Chain: associated with the optimisation of resource management in shipping, transportation and gathering of raw material, product, spare parts and components for disposal. A sustainable supply chain should be designed for environmental and cost impact minimisation; and it should be structured for both supply flows from supplier to manufacturer and customer and reverse logistics (Zhu, et al., 2008).

Design for End of Life: this category summarises all approaches and methods oriented to mitigate, reduce and eliminate negative impacts once the useful life of product is over. The End of Life (EOL) stage is considered as critical due to the need of establishing the most sustainable disposal alternative for the product or component after its useful life. EOL management is the process of converting disposed products into remarketable products, components or materials (Ramani, et al., 2010); instead of landfill, which is the most contaminant and easy way to eliminate products from the market.

2.2.2 SPD Approaches

Regarding SPD, many approaches exist dedicated to design, measure, compare and improve sustainability performance of products. Five main approaches are identified from the literature: Design for X (DFX) methods, checklists and guidelines, assessment tools, diagram tools and software based-tools. Such SPD approaches are described as follows:

Design for X methods: aims to improve and optimise particular product requirements to guarantee customer satisfaction and competitiveness. Some of the most well-known methods concerning sustainability are Design for Disassembly, Design for Remanufacturing, Design for Recovery and material recycling, and Design for Energy Efficiency among others (Rossi, et al., 2016).

Checklists and guidelines: are employed to perform a quick diagnosis related to the environmental performance of products. That diagnosis results very usefully for early design phases. The main purpose of checklist is to provide quick assessment to designers about the expected product sustainability and entails generic recommendations to decrease negative impacts in further lifecycle stages. The most employed Checklists are the Black, White and Grey list developed by Volvo (Nordkil, 1998) and the ECODESIGN Checklist method (ECM) proposed by (Wimmer, 1999). On the other hand, the guidelines are set of suggestions for designers related to improving the environmental profile of products. Several of the most widely employed guidelines are the Ten Golden Rules (Luttropp & Lagerstedt, 2006), Eco-design Pilot and the Eco-design Checklist (Tischner, et al., 2000).

Assessment tools: mainly focused on LCA, assessment tools measure the environmental, economic and social performance of products and processes. The consideration of all lifecycles phases and material and energy flows provide useful information to designers during early design phases. Commonly, assessment tools require the use of material and processes databases to perform robust analysis. Gabi and SimaPro are some of the most known LCA-based tools available nowadays.

Diagram tools: are developed to show qualitative or semi-qualitatively the assessment and comparison of results regarding sustainability indicators. According to Rossi et al (Rossi, et al., 2016), the use of diagram tools is very suitable when no detailed information about product attributes and shape is available. Some relevant diagram tools are MECO (Wenzel, et al., 1997), the Environmental Design Strategy Matrix (Abramovici, et al., 2014) (Allenby, 1994), and the Met Matrix (Brezet & Van Hemel, 1997). Some diagram tools are oriented exclusively to show graphical results and comparison between alternatives and product versions such as the Spider Diagram, the eco compass tool proposed by Johnson and Gay (Johnson & Gay, 1995) and the Eco-design Web (Bhamra & Lofthouse, 2007).

Software-based Tools: comprise the software versions of previous approaches to measure, compare and predict sustainability performance of products. Several tools are integrated to Computer Assisted Drawing (CAD) software for providing a robust analysis of basic and detailed design regarding sustainability. The most remarkable and employed tools around the world are EcoScan, Ecofit, EcoCAD, Solidworks Sustainability, Eco Audit among others.

2.2.3 Analysis of SPD Reviews

To consolidate the most representative works related to SPD, an analysis of review works is performed (see Table 1). The analysis of those review papers provides an overall overview of trends, challenges and research opportunities. Eight review papers were selected according to their relevance, the number of citations and number of works analysed.

Table 1. Analysis of Review Papers regarding Sustainable Product Design

Author	Aim-Motivation	Main Relevant Findings
(Ramani, et al., 2010) Review of Eco-design tools	To provide an overview and decision support as a key strategy	• The early design phases offer the most important impact on product sustainability. Consumer behaviour can also be significantly reshaped from early design through the designer intention. • Integration of all lifecycle stages in the implementation of sustainable design tools is always required.
(Bovea & Pérez-Belis, 2012). Review and classification of tools	To provide a guide to the designer for the selection of the best eco-design tool	• Despite the wide number of tools for integrating sustainability in product design process, the implementation is still scarce, and most of the case studies are solely theoretical-based. • Eco-design tools are not systematically implemented by companies with the required engineering rigor due to lack of environmental knowledge.
(Arnette, et al., 2014) Review of DFS techniques.	To provide an overview of DFX tools for sustainable product design.	• Most of DFX methods are focused on practitioner requirements and design goals regarding particular lifecycle stages instead of the whole lifecycle. • DFX tools can be addressed to design teams for unique requirements, but it is necessary to include holistic considerations, especially respect to product end of life stage
(Buchert, et al., 2014) Analysis and Categorization of tools for Sustainable Design.	To provide a framework that combines the advantages of different methods.	• Not all sustainable design approaches are suitable for all type of products. • Methods in conceptual stages lead to different concept decisions. Methods in embodiment stages require extensive resources and skills to perform sustainability assessments and design improvements.

Author	Aim-Motivation	Main Relevant Findings
		• Environmental dimension is predominant over the economic and social dimensions in the most of sustainability tools.
(Brones & Monteiro de Carvalho, 2015) Synthesis of theoretical contributions in Eco-design.	Integration of more effective Eco-design tools	• Integration of eco-design tools in product design requires significant efforts in the innovation and operations management. • Existing models found in literature are widely dispersed; therefore, it is complex to identify particular trends in methods and tools.
(Pigosso, et al., 2015) Review of existing Eco-design tools and methods	To identify trends and research opportunities in the next decade	• The interest in the development and application of eco-design methods and tools is growing. • Massive implementation of eco-design tools in industry is expected in future decades. • Focus on Circular Economy is remarked as a key strategy to achieve sustainability.
(Ceschin & Gaziulusoy, 2016) Evolution of DFS tools and methods	To provide a framework of evolutionary works	• The DFS tools have progressively expanded from product-based focus towards a more complex and large multi-scale system level. • Innovation in product design is strongly related to sustainability, which is considered as a socio-technical challenge.
(Rossi, et al., 2016) New literature review of the principal eco-design tools and methods	To facilitate the understanding of the main obstacles that limits their actual implementation in industrial companies.	• Companies have difficulties in the implementation of eco-design tools and methods. • The gap between eco-design and their implementation in industrial companies is increased due to the absence of knowledge of sustainability issues and the not yet significant customer and legislation pressure.
(Schöggl, et al., 2017) Summarizing of checklist tools for sustainable product development	To provide a quantitative assessment of environmental, economic and social aspects during early design phases	• Customised tools for sustainable product design are needed. • Environmental, economic and social dimensions are not integrated early in the product design phases. • An inter-functional and collaborative approach is favorable instead of assessment approaches.

2.3 Manufacturing Paradigms and Market Trends

Product manufacturing paradigms can be defined as trends that describe relationship between design, manufacturing, market and customers. It is possible to identify three main product-manufacturing paradigms along the history: Mass Production, Mass Customization and Mass Individualization. Mass Production is associated with the massive manufacturing of products with unified or fixed architecture, providing cost-effectiveness through the economy of scale. Mass Customization employs a modular product architecture characterised by modules designed and manufactured to generate different optional product choices to the customer. This manufacturing paradigm is oriented to cover different market segments. Finally, Mass Individualization involves the use of modular product platforms with a large variety of product variants resulting from the use of modules designed with compatible interfaces and high commonality.

Mass individualisation aims to generate high-personalised products (market of one). Table 2 shows a comparative summary of the main features of product manufacturing paradigms according to the definition of Koren et al. (Koren, et al., 2013), including several examples of products to each paradigm.

Table 2. Comparison of Product Manufacturing Paradigms. Adapted from (Koren, et al., 2013)

Feature	Mass Production	Mass Customization	Mass Individualization
Product Architecture	Unified or fixed	Modular	Modular Open-Platform
Product Built	Identical product	Product built with one option	Customer designed
Time Line	1913-1980	1980-2010	2010 - Nowadays
Manufacturing System	Dedicated Manufacturing Line	Flexible Manufacturing Systems	Reconfigurable Manufacturing Systems
Milestone	CNC Technology Raise	Globalization Matures	-
Examples of products	-Nut, manufactured in millions of units. -Components manufactured using extrusion.	-Portfolio of cars. -Portfolio of TV.	-Personalized PC -Personalized Surfing Table
Profit based on	Economy of Scale	Covering several market segments	Exclusivity of products

According to Table 2, product design paradigms are widely differentiated by the type of architecture, the manufacturing system, and the historical moment depending on the evolution of manufacturing technologies. Additionally, the roles of manufacturer and customers have been also changing the product design paradigm. Mass production and mass customization do not consider any participation of customer in the product development stages beyond the overall customer requirements. In contrast, the mass individualization model includes the customer requirements participation at an individual level from early design stages to achieve highly personalized products. It is even possible to reconfigure the product functional architecture in further stages such as use/operation, maintenance, and upgrading.

Cost-effectiveness of manufacturing paradigms is also very different. The mass production is based on economy of scale that is subject to the production volume. In this case, the fixed configuration product is manufactured in large batches, and the profit depends directly on the number of units sold. Mass customisation takes advantage of the modularity and sharing of constructive components to reduce the manufacturing cost and aims to cover several market segments through differentiation of products in the number of functions and capabilities from a modular product platform. Finally, mass individualisation achieves profitability through the added value of personalised products. The customer can pay for a personalised product due to the perception and feeling of exclusivity.

Regarding the differences of manufacturing paradigms from the lifecycle stages, it is possible to highlight the level of participation of both manufacturer and customer. Figure 2 describes the differences between tasks for design, manufacturing, and use for each manufacturing paradigm.

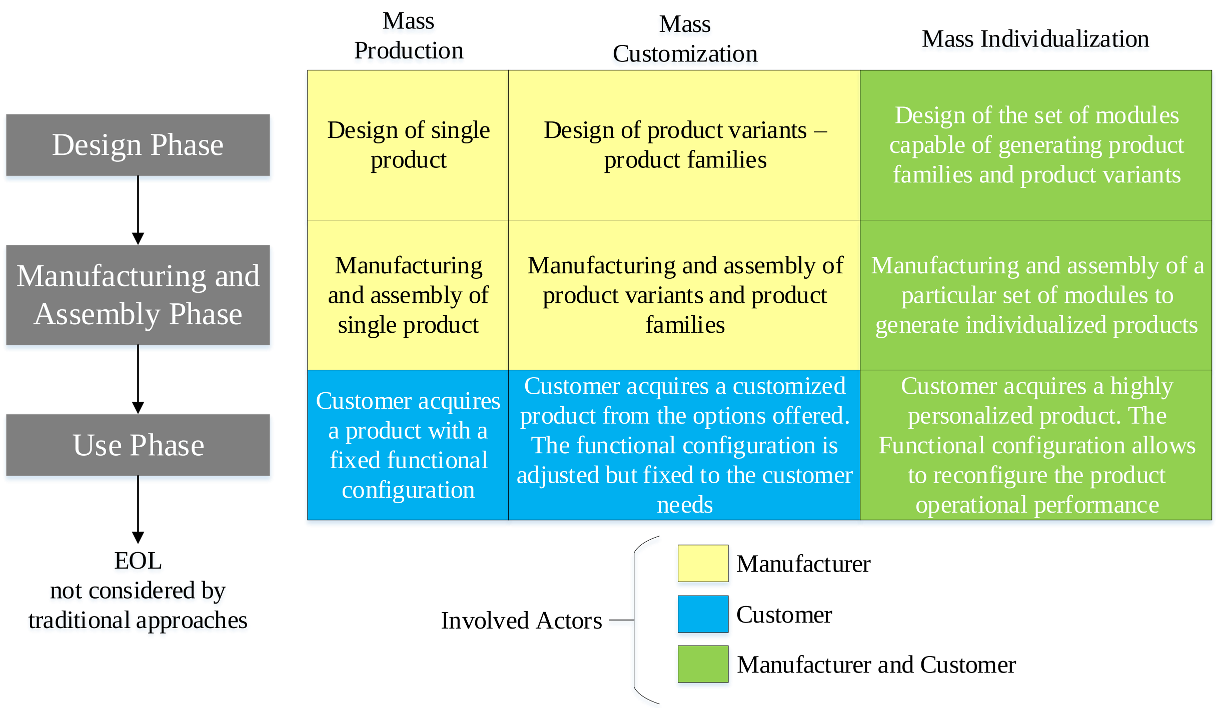


Figure 2. Comparison of strategical tasks in product manufacturing paradigms

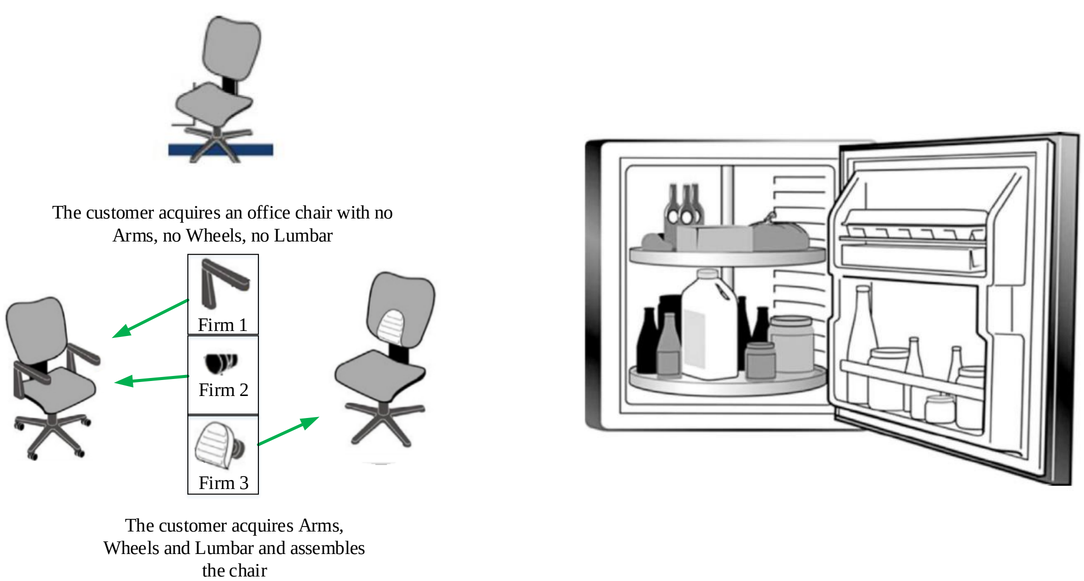
2.3.1 Open Architecture Products (OAP)

The type of products concerning the Mass Individualization paradigm are defined as Open Architecture Products (OAP). An OAP is conceived for allowing the addition, removal and exchange of constructive functional components (or modules) to generate new product features (Koren, et al., 2013). According to Zhang et al. (Zhang, et al., 2015), OAP can be considered as the products with a common basic platform, and open interfaces with different add-on modules from different sources can be connected to satisfy particular customer requirements. Feasible OAP examples are the PCs, which are designed to be updated in both, software and hardware components; the use of generic interfaces provides an easy adaptation to new peripheral components, and the robustness of operative systems entails the setup and upgrading of software tools.

The most relevant benefits of OAP can be listed as follows:

a. Provide access to potential module developers (even external to the original manufacturer) concerning to new modules for improving the product functionality and performance.
b. Standardization and commonality of modules involve cost reduction in the supply chains related to the product development and further lifecycle stages such as maintenance and final disposal.
c. Many possible modules may be invented to cover specific market segments; which improves the cost-effectiveness once the product variants are launched in the market.
d. OAP entail flexibility and variety to customers during product purchasing stage, the customers are able to choose the add-on modules from all available ones based on their particular requirements. During use stage, the customer can exchange such chosen modules (Zhang, et al., 2015).

Two examples of OAP are summarised in Figure 3, showing the architecture of the product and the possible architecture modifications provided. Figure 3a) shows a chair that can be modified through the addition of three possible modules or components; on the other hand, Figure 3b) shows the interior of refrigerators, which provide reorganisation of compartments depending on the user requirements.



a) b)

Figure 3. Examples of Open Architecture Products. a) Office chair; b) interior of refrigerators

According to the literature review, three main functional attributes concerning OAP are identified: Modularity, Reconfiguration and Product Family Approach. Each attribute is described in detail below.

Modularity: involves the functional construction of products through modules, which provide a functional platform for generating several product variants from the same basic set of constructive modules. Functionality can be improved from the perspective of both, operational range or capacity and the number of possible functions delivered by the product variant.

Reconfiguration: very related to modularity, the reconfiguration is the ability of any product of change from a particular set of functional parameters to others. This change of configuration can be performed through the adaptation of product architecture and the use of add-on modules. In product design, the reconfiguration provides high adaptability to uncertainties related to changing customer requirements.

Product Family Approach: OAP are designed to cover the same functional range and functional variety offered by a product family comprised of several product variants using fewer resources. Several product variants can be generated from the same set of constructive modules.

2.3.2 Sustainability of Mass Individualization and OAP

Regarding sustainability, each product manufacturing paradigm implicates several issues associated with the resource consumption and population growth around the world. Mass Production implies resource consumption due to the need of offering products for economy of scale, the cost-effectiveness is achieved through the sales volume, and the market demand is directly proportional to the resource consumption (raw material and energy). Mass Customization, on the other hand, involves an increase in product variety, which requires more complex and adjustable manufacturing systems able to generate several product variants and establish particular market segments, which involve a higher number of potential customers. By last, Mass Individualization through OAP entails the market of one, which represents the high personalization of products to adjust to any particular set of requirements; the resource consumption in this product-manufacturing paradigm involves then a high potential depletion of resources due to the all-possible number of customers. Such complexity of the system increases exponentially, and the product variants tend to infinity.

Mass Individualization paradigm is then, not sustainable for next generations and demands research efforts to decrease the impact on sustainability without affecting the ability to satisfy any particular customer's set of requirements. Figure 4 shows a parallel graphical comparison of both, product manufacturing attributes and sustainability issues (blue and red respectively) for OAP.

Also, Mass individualization model implies the increase of product variety to reach more customers in very personalised market segments. This product variety entails the consumption of more resources (materials, energy, and others) taking into account the population growth and its influence on the rise of individual customers in the market of one. The increase of product variety implies the need for new product manufacturing platforms, tools, and machines among others if the manufacturing system is not designed to reconfigure itself according to the customer requirements. In that case, the use of reconfigurable manufacturing systems is a mandatory alternative for developing robust product platforms capable of using a set of resources to achieve competitiveness and a cost-benefit production.

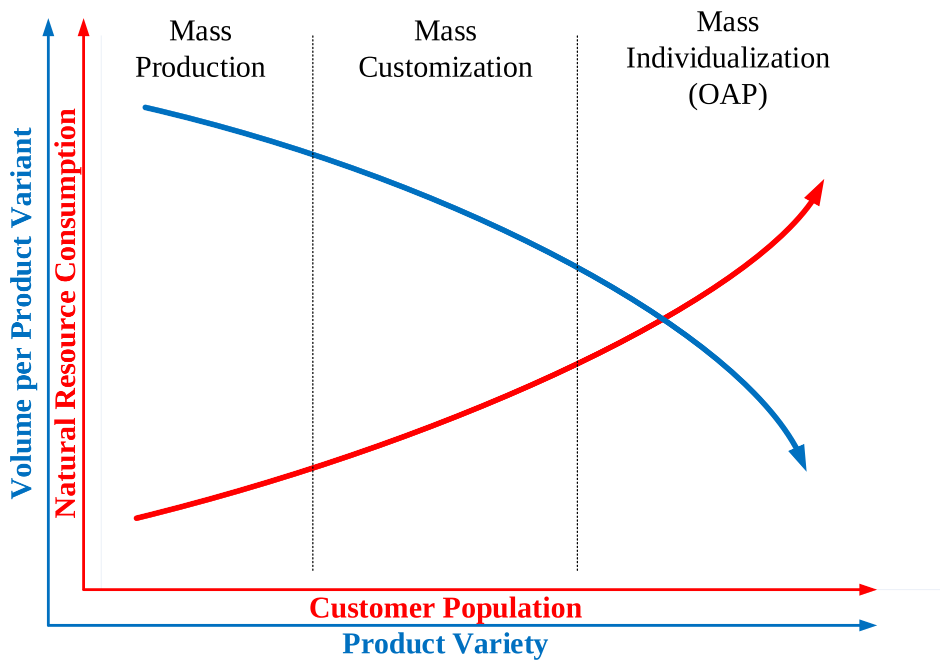


Figure 4. Relationship Product Manufacturing Paradigm and Sustainability

Sustainability impacts derived from the increase of product variety as a response to the population growth are focused in the process where it is required material transformation (material production, manufacturing, and final disposal). The main sustainability impacts identified from the product development process are listed in Table 3 including tasks associated with mass individualisation and their sources.

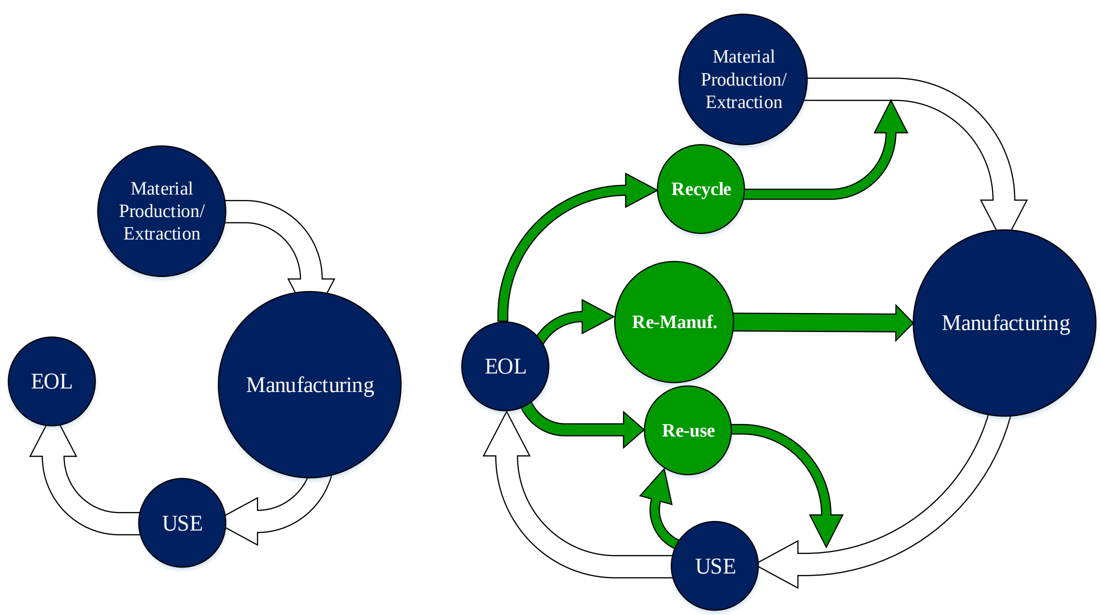
Table 3: Sustainability Impacts of Mass Individualization

Required Tasks	Sources	Overall Sustainability Impacts
Increase of variety of parts	Market (Customers in the market of one)	Increase of: • Manufacturing materials consumption
Increase of the number of products	Market	

	(Market Segment Sizes)	• Energy consumption • Emissions • Waste materials • Complexity of end-of-life (EOL) Stage Management • Increase of demand for material production
Specific modules required during the use stage	Customer (Customer wishes)	
Increase of variety of miscellaneous requirements	Customer (Additional requirements)	
Reduction of ramp-up time between product family versions	Market & Companies (Accelerated Consumption Culture)	

2.4 Circular Economy (CE)

The Circular Economy (CE) concept can be defined as a model in which the flow of energy, materials, and resources are related in loops to minimize emissions during the whole lifecycle of products and services. Unlike the traditional or linear economy models that have not loops among the lifecycle, the design for sustainability is closely linked to circular product design. This is due to the common aim of increasing positive impacts, and reducing negative impacts derived from any product development process such as adverse outputs (e.g., emissions and waste released to the environment in the air and landfills.) Figure 5 shows a graphical comparison between linear and CE models. Recycling, reuse and remanufacturing are highlighted as feasible tasks to reduce adverse impacts during the lifecycle of products.



a) Linear Economy   b) Circular Economy

Figure 5. Comparison between Linear and Circular Economy Models. a) Linear Economy; b) Circular Economy

2.4.1 CE Key Strategies

According to the existing information in the literature, five main key strategies can be identified concerning CE:

- Design for circular supplies: focused on the thinking of generating similar cycles to biological process in which the resources are obtained and returned to their natural cycle without harming the environment (Benyus, 2002). This strategy also involves the generation of internal supply chains between stages of the product lifecycle, which extend the useful time of products and components.
- Design for resource conservation: oriented to develop products using the minimum possible resources from a preventative approach (Bocken, et al., 2016). This goal can be achieved through an optimised selection of materials and a robust design process to provide suitable geometries and manufacturing materials.
- Design for extended life use of products: aimed to extend the utilisation of a product during its use phase through activities such as reuse, repair, easy maintenance and upgrading (Bakker, et al., 2014). This strategy involves a robust product design oriented to manufacturing, assembly and disassembly; and the modularisation and standardisation of components and interfaces.
- Design for multiple cycles: focused on the use and circulation of material and resources in multiple cycles (Bocken, et al., 2016), (Bakker, et al., 2014). This strategy involves the remanufacturing, reuse and product sharing. The multiple useful cycles allow taking advantage of the full useful time expected from the design phase, and components can be helpful for their partial or complete failure.
- Design for systems change: associated with the whole spectrum of value creation for both biological and technical cycles; this includes the development of innovative solutions to adapt product features to market changes (Charnley, et al., 2011).

2.4.2 Attributes of Circular products

After the definition of key strategies of CE, three main attributes related to the enhancement of sustainability and functionality are identified. These attributes are:

Design for EOL: The decision making at the end of life of products represent the most critical stage which should consider all negative impacts of landfill and the challenges involved in the recycling, reuse and remanufacturing of products and parts. The circularity of products is most relevant at EOL phase due to the end of product lifecycle can represent a new beginning in previous stages such as manufacturing and use.

Extension of Useful Life: circularity is improved when product components and the whole product stay the most useful time as possible even circulating after recycling, remanufacture and reuse. Short circular cycles are not desirable due to the need for energy consumption and resources to introduce them again into a new lifecycle. The ideal scenario consists of circular cycles with a long extension which provides the possible intensity of use.

Lifecycle Thinking: each constitutive component or module in the product must be designed to be reused, remanufactured and recycled regarding EOL. Respect to other stages such as maintenance and upgrading, the product requires providing easy assembly and disassembly tasks for facilitating a cost-effectiveness coupling and decoupling of modules. In other words, the product must be designed considering each module as a circular component, which can be integrated into the product due to functional requirements, maintenance and upgrading tasks and EOL alternatives.

2.5 Trends and Perspectives

Design attributes from OAP and CE are strongly related, and such relationships can be used as research opportunities to improve sustainability performance of products. Figure 6 shows the identified relationships mentioned previously. Further description of each relationship is also defined below.**¡Error! No se encuentra el origen de la referencia.**

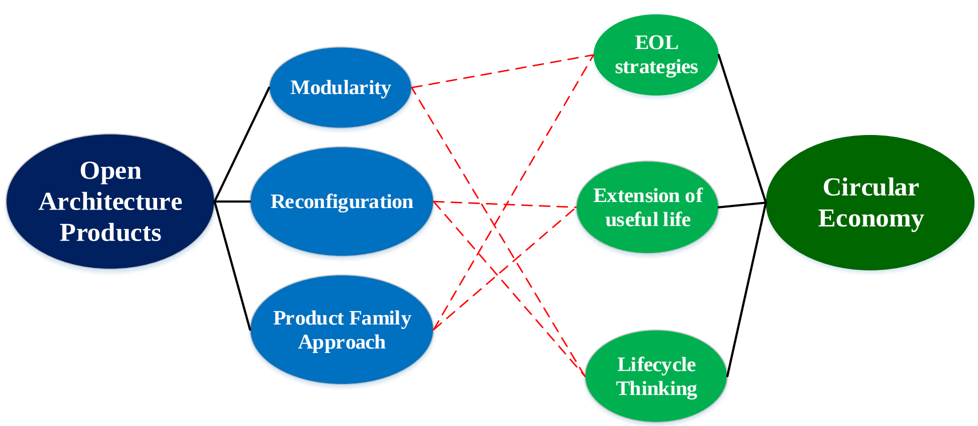


Figure 6. Relationship between Open Architecture Products and Circular Economy

a) **Modularity – EOL, Lifecycle Thinking Relationship:** modularity entails substantial benefits to the CE from the perspective of EOL through the simplification of assembly/disassembly task to facilitate the separation and removal of components. Regarding the whole lifecycle, the modularisation provides easier maintenance, repair, and exchange of components through the standardisation of interfaces. Additionally, the modularity allows upgrading the number of functionalities and operational ranges of the product centring the modularisation on particular functional component responsible for functions and operational levels

b) **Reconfiguration – Extension of useful life, Lifecycle Thinking Relationship:** the reconfiguration of products consists of the change of constructive and functional components to adjust to new operational requirements, such change of configuration can be considered an upgrading to achieve a new product variant. The concept is associated with the optimisation of resources and the comprising of product family functionalities into a single product; therefore, the useful life of the product can be diminished due to the intensity of use required. The reconfiguration also entails an enhanced lifecycle management of constructive components of products due to the existing modularisation among them.

c) **Product Family Approach – Extension of useful life Relationship:** the design of a product family provides the implementation of modules sharing among each product variant when the customer requires to increase the operational range of the product or to add new functionalities to the product. The standardisation and commonality among products facilitate the extension of the useful life of products through the reuse of modules; this scenario is possible when the product family is designed to operate as a modular product.

Regarding the implementation of Circular Economy in OAP, a literature review is performed focused on the approaches related to sustainable product design. Regarding OAP, the existing approaches are limited and are under development. Just few research works on design can be remarked such as the one by Zhang et al. (Zhang et al., 2015) that proposes a design method for adaptable OAP, and the work by Ma et al. (Ma et al., 2017)that establishes a method to determine the optimum assembly sequence planning for OAP.

Due to the lack of research identified in the literature, existing product design approaches are analysed and assessed aiming to establish the most suitable and promissory works regarding product sustainability improvement concerning OAP and CE. Table 4 shows 17 research works associated with main attributes of OAP and promissory application towards the integration with CE.

Table 5 summarises the degree of applicability for each approach taking into account the attributes for both OAP and CE described previously.

Table 4. Characterization of authors in Sustainable Product Design related to OAP

Author	Method/Approach	Aim
(Vanegas, et al., 2017)	eDiM – ease of Disassembly Metric	Method for measuring and facilitating disassembly to improve reuse, recycling and remanufacturing.
(Paterson, et al., 2017)	End of life decision tool for remanufacturing	A tool for supporting the making decision concerning EOL strategies.
(Kim & Moon, 2017)	Sustainable platform identification	To identify the sustainable platform for a product family.
(Favi, et al., 2017)	Design for EOL approach	To help designers in the evaluation and subsequent improvement in product EOL performance
(Yu, et al., 2015)	QFD and Modularity for EOL of product family	To develop a design method for eco-issues and product family issues.
(Wang, et al., 2015)	AHP-based eco-design model	To help designers to decide for evaluating eco-design options
(Sakundarini, et al., 2015)	Modular design method	To optimise EOL strategies by using an Excel-based approach.
(Pialot, et al., 2015)	Eco-innovative method based on upgradability	To explore upgradability possibilities and to specify and assess upgradable systems.
(Osorio, et al., 2014)	Product design approach based on DFX guidelines	To gather the main product design requirements for developing sustainable mass-customised products.
(Chou, 2014)	ARIZ-based life cycle engineering model for eco-design of products	To restructure a set of new product models using modular analysis, to develop an effective assessment method, and to search for improvement opportunities.
(Mascle, 2013)	Methodology for product rebirth	To enables product design according to objectives defined by its end of life (EOL).
(Zwolinski, et al., 2006)	Design Method for re-manufacturable products	To propose an approach for integrating remanufacturing constraints throughout the design process.
(Gu, et al., 2004)	Method and guidelines for adaptable design	To provide a framework concerning adaptable design and its benefits.
(Kimura, et al., 2001)	Product Modularization Strategy	To design based on product functionality, commonality and lifecycle similarity.
(Koga & Aoyama, 2008)	Method for design of modular products based on its lifecycle	To design the optimal modular structure considering life-cycle calculation based on the sales of the line-up products in the product family.
Umeda (Umeda, et al., 2005)	Function Behavior State Modeling	To define candidates of modification of the function structure and configuration of an upgradable platform for modular products.
Yang et al. (Yang, et al., 2014)	Method to design eco-product families through modularity	To provide a systematic method to develop an eco-product family is proposed to improve the reusability and recyclability of waste products.

Table 5. Applicability of design approaches regarding OAP and Circular Economy

	Main Topics	(Vanegas, et al., 2017)	(Gu, et al., 2004)	(Chou, 2014)	(Kimura, et al., 2001)	(Mascle, 2013)	(Yang, et al., 2014)	(Wang, et al., 2015)	(Zwolinski, et al., 2006)	(Yu, et al., 2015)	(Osorio, et al., 2014)	(Pialot, et al., 2015)	(Sakundarini, et al., 2015)	(Kim & Moon, 2017)	(Paterson, et al., 2017)	(Favi, et al., 2017)	(Koga & Aoyama, 2008)	(Umeda, et al., 2005)
	Applicability	**M**	**H**	**L**	**H**	**H**	**M**	**L**	**L**	**M**	**M**	**L**	**L**	**M**	**L**	**L**	**M**	**H**
OAP	Reconfiguration		X								X							
OAP	Product Families		X		X	X	X			X				X			X	X
OAP	Modularity		X	X	X	X	X		X	X	X	X	X	X		X	X	X
CE	EOL	X		X	X	X	X		X	X	X		X		X	X		X
CE	Life Cycle Thinking	X			X	X		X						X				X
CE	Extension of Life Cycle	X										X						

Applicability levels: H- High; M- Medium; L- Low

According to

Table *5*, none of the approaches founded in literature fulfill the six attributes from OAP and CE. However, the analysis developed in

Table *5* entails further research opportunities to integrate new concepts to achieve robust approaches concerning OAP design for the CE model. Reconfiguration, Lifecycle thinking and extension of lifecycle are the weakest research topics founded in the literature; on the other hand, modularity, EOL and product families are common among the analyzed works. Finally, modularity is remarked as the most common attribute among works analyzed, this is due to the need of decoupling products in separated functional units in the OAP philosophy.

2.6 Research Opportunities

This subsection describes the trends and research opportunities regarding mass individualization, sustainability, OAP and circular economy. From the analysis of research opportunities is possible to identify promissory research works focused on the DFS considering OAP and CE from a holistic perspective.

2.6.1 About Sustainable Product Design

a. The integration of socio-economic issues with environmental aspects. The environment is the most relevant dimension studied according to the results and discussion of review papers analysed regarding sustainable design. Several works consider the economic dimension and just a few the social aspect (Ramani, et al., 2010) (Arnette, et al., 2014) (Pigosso, et al., 2015).

b. The development of multiple lifecycles and CE strategies is highlighted as potential trends by (Ramani, et al., 2010) (Pigosso, et al., 2015) (Rossi, et al., 2016). Optimization of products during lifecycle interactions in manufacturing, use, and final disposal are remarked as key issues to enhance the sustainability performance of products and industrial companies.

c. Practical case study applications of DFX tools concerning sustainability. The vast majority of approaches has not been validated in the industrial field. Although most of the works are validated through particular case studies (Arnette et al., 2014) (Brones & Monteiro de Carvalho, 2015) (Pigosso et al., 2015) (Rossi et al., 2016).

2.6.1 About Circular Economy and Open Architecture Products

a. The use of common modules and interfaces in OAP entails suitable supply chains among the product lifecycle stages, especially from End of Life (EOL) to previous lifecycle stages such as use and manufacturing. The implementation of such supply chains stimulate the circularity of components and hence the circular economy model.

b. The circularity of products and components are strongly related to decision making in final disposal or EOL, and the design process can be oriented to facilitate the most sustainable EOL alternative among recycling, reuse and remanufacture. The OAP may be designed to facilitate an easy assembly and disassembly tasks to guarantee a suitable EOL.

c. Designers can influence the customer/user thinking through the product design attributes. Strategies such as persuasive design can be implemented from early design stages for establishing the reuse and exchange of modules during product lifecycle. However, this issue need also an educational work and mind changing of customers/users.

d. OAP can be designed considering particular EOL for each constructive component. The selection of materials and manufacturing processes need to be selected carefully to obtain desirable durability according to the expected useful time considering the circularity of each component and whole sustainability impacts.

e. Lifecycle Analysis of OAP involved several new aspects that need be considered such as intensity of use, reusability of components, design for assembly/disassembly cycles, availability and maintainability of critical modules, interface and connectors robustness and design for durability according to the functionality and expected useful life of components.

f. Reconfiguration, lifecycle thinking and extension of lifecycle are considered just by a few works in the literature. Therefore, further research efforts should be addressed to cover these aspects to provide higher robustness of product sustainability performance.

2.6.2 About Modularity

a. Modularity is one of the most widely employed concept to design OAP. Therefore, it is mandatory to include modularity considerations towards the integration of circular economy into the product design process for OAP.

b. The design of modularised products can be used to apply the key strategies of Circular Economy in the product development process. Especially, in the design of product families which involve the use and sharing of common modules.

c. The use of modular design requires formal methodologies to establish the most sustainable product architecture for each component. Particularly, in the case of product families, traditional design methods do not consider sustainability issues in the definition of the product architecture.

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Chapter 3

Modularity Strategies for Sustainability

Highlights

- Design strategies for sustainability based on modular architecture principles are proposed
- Modular Architecture Principles – MAPs are characterized from the perspective of sustainability for the design of Open Architecture Products
- Desing considerations for Open Architecture Products are suggested.

Contents

3.1 Introduction

Modularity is considered a key concept in the product development in the current globalised market. The use of modularity, especially in the manufacturing stage, provides flexibility for the development of product variants involving few changes in the same fixed manufacturing resources. Since the last decade, the use of this concept has been extended to all stages of the life cycle of products through Open Architecture Products (OAP), which employs modularity as a transversal tool across the product lifecycle to increase the encompass of many customer niches (Jian et al., 2016). Nevertheless, the modularity is included just as a whole strategy for adding, removing and interchanging functions. The approaches that include modularity as a sustainability tool do not consider the different ways to modularise a product, the variety of architectures available, and their consequences respect to the overall sustainability performance of products.

This chapter provides highlights in the use of Modular Architecture Principles – MAPs in the design of products based on the Mass Individualization model. Five strategies to enhance sustainability are also proposed taking into account the usefulness of modularity in the OAP, which is considered the most competitive and cost-effective model to face the changing customer requirements and meet the personalisation demanded in the globalised markets. The approach described in this chapter is used as a theoretical framework for the proposed methodology described in chapter 4.

3. 3 Modular Architecture Principles (MAPs)

In the product design field, Modularity is defined as the use of standard units to create product variants. Modularity is achieved when the product development process is based on independent, standardised or interchangeable units to satisfy a variety of functions (Huang & Kusiak, 1998). Nowadays, it is possible to identify several main architectures or arrangements to include modularity into the product design processes. Such architectures are denominated Modular Architecture Principles – MAPs.

Modular architecture principles – MAPs are strategies to develop the structure of a product based on the needs in design, manufacturing, use, and final disposal. According to Mesa et al. (Mesa et al., 2015), it is possible to identify more than ten modular architecture principles in the literature review. MAPs can be employed to facilitate the adaptation concerning work ranges and the number of functions required by the type of product or product family. A classification of the most representative MAPs is proposed in this work taking into account the functionality of each principle. The classification of MAPs is described in detail below, and examples of each MAPs are shown in the next subsection.

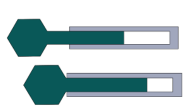
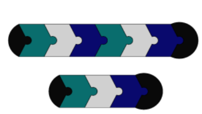
3.3.1 Functional Characterization of MAPs

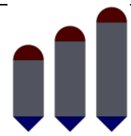
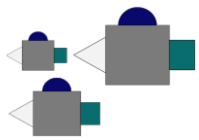
The classification proposed in this work is oriented to separate the type of MAPs according to the main benefits and common uses. The proposed classification aims to facilitate the identification, selection, and understanding of MAPs during the early design of products and product families. The selection and implementation of these principles affect the remaining stages of the product lifecycle significantly. MAPs can be classified into two main groups or categories: Functional Ranging and Functional Variety (Mesa et al., 2015). In the Functional Ranging type, products develop a unique function in different working levels; e.g. a set of motors with different horsepower performance (all the products have the same function but different levels). On another hand, the Functional Variety is associated with the development of several functionalities in a single specific range; e.g. a Swiss Army knife which can perform different tasks (blades, screwdriver, scissors, can opener, corkscrew, and so on.) It is important to clarify that it is possible to combine MAPs from the two categories aforementioned. However, those mixed principles are not considered in this work.

3.3.1.1 Functional Ranging MAPs

Functional ranging MAPs are related to the variation of particular functions or parameters in size or operational range. Principles of this category provide different ways to satisfy several levels of capability respect a particular function depending on the levels identified in the customers' requirements. It is possible to select an adequate principle of functional ranging or to combine them to reach a particular sizing according to the case. The sizing can be done through constant discrete steps (stacking, cut to fit, size range), random sizes (cut to fit) and continuous (adjustment – that also can be used in discrete values). The benefits associated with the reach of different levels of work in functional ranging depend on the robust design of the standard interfaces and connectors, especially in stacking and cut to fit principles. Table 6 describes the principles of this category.

Table 6: Functional ranging MAPs, adapted from (Riba, 2002), (Ulrich, 2004)

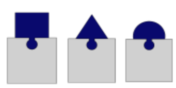
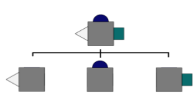
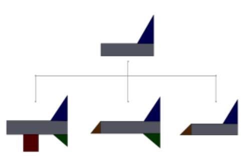
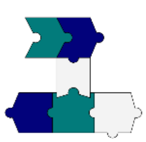
MAP	General Scheme	Description
Adjustment		A single module provides adjustment to reach different adaptation levels within a working range. This principle offers the possibility of performing a continuous adjustment in the functional level within a predefined range. The application of this principle is commonly observed in the use stage.
Stacking		Several identical modules can connect with each other in a stack structure to provide stepped increases respect to one parameter. Levels of the discrete adjustment are multiple of the added modules and are commonly employed in the assembly and use stage.

MAP	General Scheme	Description
Cut to Fit		Modules manufactured to fit can be interchanged to provide a customization in particular functional levels.
Size Range		A set of modules can vary in one or more parameters. The modules carry out the same function at different levels. Product variants do not share physical components but design and manufacturing resources (design libraries, parametric design models, manufacturing processes, etc.)

3.3.1.2 Functional variety MAPs

In this category, the principles are related to the addition, substitution or removal of various functionalities in products. The change of dedicated modules with specific functions are allowed in both, single functionality (Component Sharing, Component Swapping) and several functionalities (Widening, Narrowing). This classification also considers the ability to generate different configurations from a unique product (Sectional). Table 7 summarises the MAPs corresponding to this category.

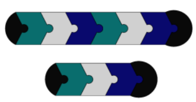
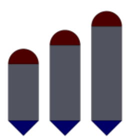
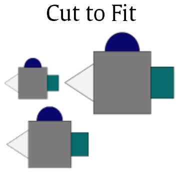
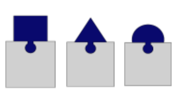
Table 7: Functional variety MAPs adapted from (Riba, 2002), (Ulrich, 2004)

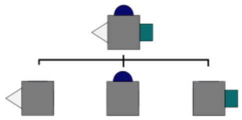
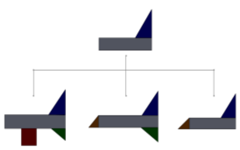
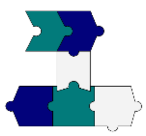
MAP	General Scheme	Description
Component Sharing		Varied platforms are designed to share a common module to generate different product variants.
Component Swapping		A set of modules with different functionalities is designed to be integrated to a base component or platform through the same interface.
Widening		A unique module-based arrange is designed to satisfy all the possible product variations.
Narrowing		A minimum standard module is designed to substitute all the possible modular adaptations in which there are more components involved.
Sectional		A set of modules can connect to others in different configurations to provide configurations with different functionalities.

3.3.2 Examples of MAPs Implementation

Examples for MAPs implementation in conventional products and product families are summarised in Table 8, which also includes a brief description of the product functionality and the advantage provided by each principle.

Table 8: Examples of MAPs implementation in products

MAP	Example	Description
 Adjustment	 Adjustable Wrench	Adjustable wrench replaces a family of wrenches. Instead of changing between wrenches, the adjustable wrench can increase or decrease the size of the jaw.
 Stacking	 Silos by Stacking	Stacking modules can achieve different operational sizes. In this case, the same common and constructive unit can be used for generating several sizes of silos.
 Cut to Fit	 Plotters	The use of cut to fit allows to construct several sizes of Plotters; the lateral and supporting components are the same in each configuration.
 Size Range	 Bicycle Product Family	Size ranging in bicycles provide a particular and complete product variant for each required size. The functionality is the same and varies according to the user growth.
 Component Sharing	 GoPro® & configurations	The GoPro® camera can be adapted to different systems to achieve its functionality to particular scenarios. The function for the shared module (the camera) is the same; the variation is concentred in external components.
 Component Swapping	 Mixer	The mixer can develop its function using interchangeable sets of blades, the form and size of the output material depend on the set of blades installed. All the sets of blades are connected to the same interface and joining method.

MAP	Example	Description
 Widening	 Swiss Knife	The Swiss Knife® can integrate many different functions in a unique product variant. In the example shown, the product provides knife, scissors, and sandpaper tool. This product variant mixes three products in one.
 Narrowing	 Handheld Rig	The showed handheld rig, and the light and monitor accessories can be integrated with the main core component, in this case, the camera. The possible configurations provide flexibility according to the needs of the user.
 Sectional	 Multiconfiguration Byke (UPSTART, 2016)	The Multiconfiguration Byke® is a product able to configure in at least three user configurations and an additional transporting array. The configurations are achieved using the same core set of modules.

3.4 Design Strategies for Sustainability based on MAPs

In this section, five main strategies or interventions are proposed taking into account the benefits/limitations of MAPs to develop products or product families, especially for mass individualisation products. The strategies are actions that combined with MAPs enable a reduction of negative impacts regarding the environment, economy, and social dimensions. The focus of these strategies is the use of minimum resources to achieve the desired performance of different product variants through an open architecture platform. In addition, the proposed strategies entail benefits such as manufacturing time, product family complexity and the circularity of reusable components. The strategies are described in detail below.

3.4.1 Reuse of Modules

Modular products are suitable for reuse modules not only between the final disposal and manufacturing stage but also in use stage or operation. In the manufacturing stage, the responsible is the manufacturer, which requires a specific supply chain to receive and classify the parts from the final disposer. In the case of the use stage, the responsible of re-incorporate the used part is the customer.

In the latter case, the consciousness and sustainability perspective is strongly needy. Both scenarios are described in detail below.

Reuse by the Manufacturer: the reusability in the manufacturing stage provides benefits such as the reduction of raw material, processing energy, manufacturing time and all costs associated with these tasks. In the case of OAP, the requirements of supply chains and management of components are the same than regard to conventional products. The used part is commonly used in a refurbished product and cannot be offered as a new part.

Reuse by the Customer: commonly, the disassembly operator and re-manufacturers reuse components and customers do not have any responsibility (Lu et al., 2014). In the case of OAP, it is possible to reuse components in both stages manufacturing and use. The modularity of the product should be able to provide an easy addition, removal or modification of modules. In the use stage, the reusability provides savings to the user related to the cost of spare parts and extension of the useful life of products. Reusable parts in the use stage can also be considered as spare or refurbished parts.

3.4.2 Robust Selection and evaluation of MAPs

According to Kimura et al. (Kimura et al., 2001) is complex to introduce reused parts based on a conventional product structure. For this reason, it is necessary an appropriate product modularisation that provides the enhancement of the product management in its life cycle. The identification and selection of the most suitable MAPs according to the design requirements are critical, taking into account that several principles can be employed to modularise a component. For this reason, a systematic and analytic selection process of MAPs is highly recommended. For these tasks, Mesa et al. (Mesa et al., 2015) have developed a functional characterisation of MAPs; however, it is necessary to consider sustainability issues and benefits of each principle as well.

3.4.3 Design for Common Interfaces

Modular products are designed to be easily assembled and disassembled; therefore, the selection and design of joints and interfaces between modules are critical. An ideal modular product should be designed using a common system of interfaces. This feature facilitates and standardises the assembly/disassembly tasks and, consequently, provides savings in the lifecycle stages where adding, substituting and removing modules is required. The interfaces of modular products are critical not only in the manufacturing and final disposal stage but also in the user stage. The tasks related to upgrading, maintenance and module addition/removal are critical as well. The reusability is highly related to the design of interfaces. A poor interface design entails the excessive use of time and resources in the modularisation tasks during the manufacture, use, and final disposal stages.

3.4.4 Actions for Corporate Responsibility

The manufacturer and final disposer should develop alliances and formal supply chains to guarantee the reuse and recycling of modules. The recycling provides raw material that can substitute raw material from primary sources, and the reuse minimises cost in the manufacturing of refurbished products. An ideal model of sustainable product development includes a direct supply chain from the final disposer to the manufacturer or the creation of a productive unit in charge of receiving, classifying and shipping parts to the manufacturing and assembly lines in the case of reusable products.

In the case of recycled material, this should be shipped to the material producer or the manufacturer depending on the primary form required in both stages. The recycled material can substitute the raw material from primary sources, although can represent impacts on the processing costs. In the latter scenario, the use of educational and consciousness campaigns can be implemented to explain to the customers about recycled materials and the reasons for the cost increase associated with the final product.

3.4.5 Actions for User Responsibility

The user in the modular product platform has the most important responsibility concerning sustainability. Once the product passes to the customer, the user is responsible for the correct use of the product and the adequate final disposal when it is necessary. The user consciousness is the main objective of this strategy, and the sustainability success in subsequent lifecycle stages depends in large part on the user decisions. Since the use stage involves upgrading, maintenance and addition/removal of modules, it is ideal at this stage to receive reused parts, spare parts and to provide an adequate maintenance schedule in the case of MAPs with functional centralisation or complex disassembly processes. Besides, the user should carry the product to the final disposer, facilitating the cycling of resources. Another important aspect related to consciousness is the recycling culture and the awareness of acquiring products from companies with sustainability responsibility. For instance, companies with supply chains from the final disposer and material producer that guarantees the cycling of the material and its waste generation.

3.5 Benefits and Limitations of MAPs

The use of MAPs involves important considerations through the lifecycle of the product. The main sustainability enhancements are focused on the reduction of material and energy during the manufacturing stage, which also is related to the reduction of required energy in the final disposal stage to convert the product into raw material. From the perspective of product manufacturing paradigms, modularity is employed in mass customization and mass individualization (OAP) models, however, the modularity approach and relevance varies significantly between those models.

In the case of OAP, It is possible to identify a benefit cycle between final disposal stage and manufacturing and use stages, the reuse and commonality of components can be seized to extend the product use stage and diminish the roadmap and replacing time of products. Figure 7 summarises the potential benefit cycle in OAP and its comparison respect modular architecture products (mass customisation).

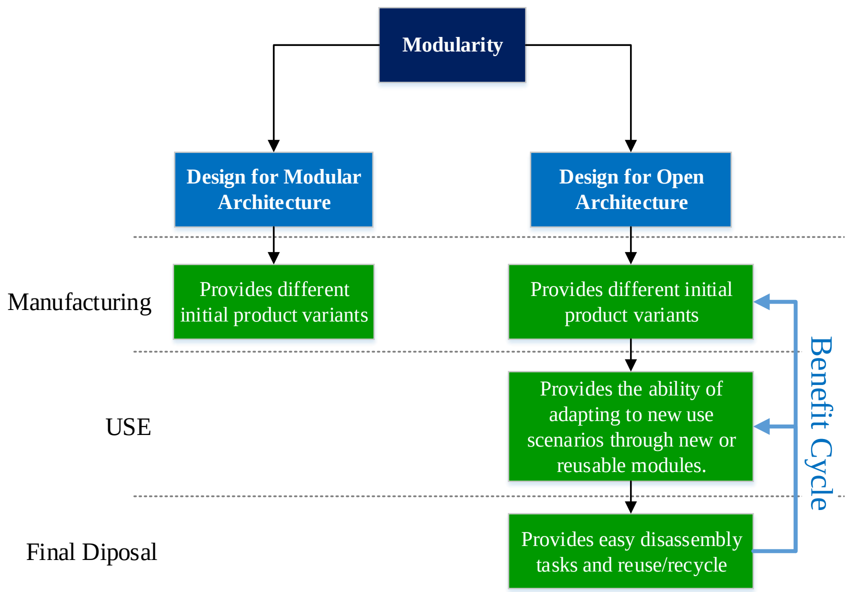


Figure 7. Lifecycle advantages of MAPs in Modular and OAP

Current product development processes are centred in the generation of product families, which involves the use of product platforms, defined as the set of hardware, software, and resources related to the development of products. Conventionally, the product families are designed taking into account a differentiation in market segments, users, special requirements and feedback from users, manufacturers and all the actors associated with the development process. Each product variant is not related or linked to the others. Once the product leaves the manufacturing stage and the following stages of the lifecycle (Use and Final Disposal), it is isolated and conceived without any relationship with the origin product platform and the rest of product variants.

Among the attributes of MAPs in open architecture, there are three specific aspects of interest. The first aspect is reusability, related to the reuse of modules between the use, final disposal and manufacturing stages. Regarding this aspect, some MAPs are preferable such as stacking or component swapping, in which the modules are not employed all the time and the interchange of modules implies standby times for those modules that are inactive. MAPs such as adjustment or widening involve the use of the adjustment module for all possible configurations. Due to this, its relative useful life is shorter compared to interchangeable principles.

The second aspect is the modular independence, associated with the ability of functional modules of work in another product variant when they are not used in the current product configuration. For example, modules of widening principle cannot work in another product variant because all the modules are integrated into the same product, whereas the stacking modules can be shared with another product variant simultaneously.

The third aspect is the ability of the MAPs for replacing a family product. From the perspective of sustainability, this is the most significant benefits. The integration of different functionalities and levels provides the replacement of product families by a single modularised product variant. For example, it is possible to replace different product variants through a unique product with the adjustment. For example, an adjustable wrench replaces a family of wrenches. The widening principle also provides the integration of several products in one, e.g. the Swiss Army knife replaces knife, scissors, and corkscrew among others by a unique integrated product.

The most common limitation of the use of MAPs is the functional centralisation of modules, which means dependency of other modules to achieve the desired function and the idle time associated with it. However, the use of MAPs can be improved by increasing the reliability of components and following adequate maintenance tasks. Table 9 summarises the benefits, limitations and sustainability impacts of the MAPs implementation in product development. Table 10 sums up the reusability, modular independence and the ability of family product replacement.

Table 9: Sustainability Benefits, Impacts, and Limitations of MAPs

MAP	Benefits – Advantages	Sustainability Enhancements	Limitations
Adjustment	A single product can replace a set of products with different performance levels respect to a function.	The potential reduction of consumption of resources (Materials, and Energy) in the manufacturing and final disposal stages.	High Functional centralisation, all the resources are focused on a single product; the reliability of the product is critical.
Stacking	The user through the stacking of components can construct a set of products with different performance levels respect to a function.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages. A stacking module can be used in different product variants through the same connection interface.	Functional centralisation, the stacking modules are useless when they are not working in the product construction. The ranging is just achieved in discrete intervals or stepped values.
Cut to Fit			

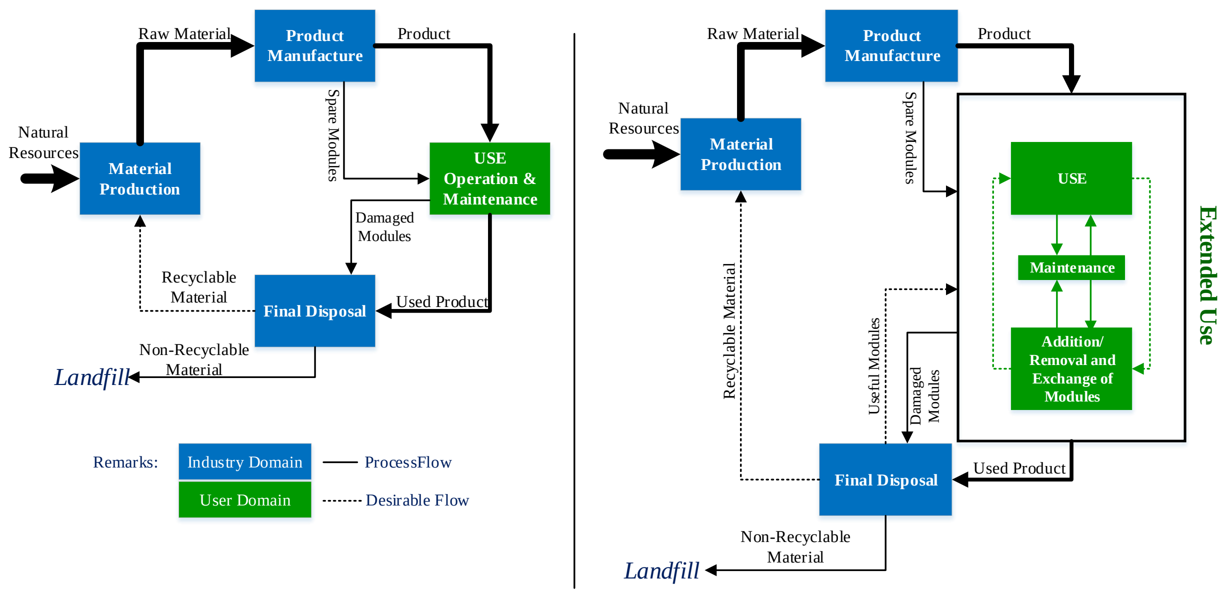
MAP	Benefits - Advantages	Sustainability Enhancements	Limitations
	The user through the exchange of specific modules in which the ranging is focused can construct a set of products with different performance levels respect to a function.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages. A cut-to-fit module can be used in different product variants through the same connection interface.	Functional centralisation, the cut-to-fit modules are useless when they are not working in the product construction. The ranging is just achieved in specific values; it is necessary to define the values of variation previously.
Size Range	A set of products is developed at different levels or scales. Each product with its modules is established for each level.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages.	The use of different components carries more complex manufacturing and final disposal processes.
Component Sharing	A set of products shares the same module, which can be integrated using a standard interface. The functionality can share with many or all product variants.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages. The common module can work in different product variants.	Only a product can employ each sharing module at a time.
Component Swapping	Specific modules with particular functions are designed for integrating different products though	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages. The common module can work in various product variants.	Only a product can employ each swapping module at a time.
Widening	All the possible functional variations are integrated into the same product.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages.	High Functional centralisation, all the resources are focused on a single product; the reliability of the product is critical.
Narrowing	All the possible functional variations are established around a same minimum sharing component. Additional functional modules can be added in each product variant.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages.	High functional centralisation, all the resources are focused on a single product; the reliability of the product is critical.
Sectional	Product variants (associated with product configurations) are achieved through the reconfiguration of constructive modules.	Reduction of consumption of resources (Materials and Energy) in the manufacturing and final disposal stages. The definition of configurations requires very conscious design, the selection of interfaces is critical.	All modules are essential; all the configurations depend on the same set of modules. If one module it is not working this can affect the performance of the product in different configurations.

Table 10: MAPs respect Reusability, Modular Independence, and Family Product Replacement

MAP	Category	Reusability	Modular Independence	Family Product Replacement
Adjustment	Functional ranging	Limited	No	Yes
Stacking		Yes	Yes	Yes
Cut to Fit		Yes	Yes	Limited
Size Range		No	Yes	No
Component Sharing	Functional variety	Yes	Yes	Yes
Component Swapping		Yes	Yes	Yes
Widening		No	No	Yes
Narrowing		Yes	No	Yes
Sectional		Limited	No	Yes

3.6 OAP Considerations

The design for open architecture includes additional considerations related to the lifecycle stages. In this case, products are characterised by the use of common parts and the exchangeability of components during the use stage, and by design for an easy assembly/disassembly that provides the planning of final disposal for each module as independent, facilitating the product modification in the use stage. Even it can include the possibility of upgrading components (new modules associated with specific functions or levels) at the use lifecycle stage. Additionally, the open architecture enables the extension of the useful life of the whole product. This feature is possible because this approach allows designing products to achieve the operation range or the necessary functions using fewer components due to the sharing and swapping of modules through common interfaces. A comparison between the life cycle of conventional modular and OAP is summarised in Figure 8.



a) Lifecycle of Modular Product Family

b) Lifecycle of Open Architecture Product Family

Figure 8. Lifecycle Comparison between modular and OAP. Figure 1a) and Figure 1b) correspond to Stages for modular product and stages for OAP respectively.

3.7 Sustainability Characterization of MAPs for OAP

According to the strategies for sustainability identified from MAPs, it is possible to establish a preference for modular principles depending on the functional requirements (variation or range of functionalities). In this subsection, two hierarchies are established from the definitions and features of MAPs previously summarised in Table 9. The hierarchy is proposed taking into account the existing trade-off between functionalities and resources involved in each MAP.

3.5.1 Functional Variation Hierarchy

MAPs for functional variation are classified in a preferable order according to the sustainability performance and functionality requirements for product families based on growth paths. Figure 9 shows the flow diagram for the functional variety MAPs in descending order from the most preferable up to the less preferable. Besides, the design strategies for each MAP are described below.

a) Widening: to design the product family based on a unique configuration arrangement capable of integrating all functionalities required through non-separable modules. Each function is achieved by a particular module, and several functions can be performed simultaneously without need of decoupling modules. This MAP facilitates the use of all required functionalities as long as the user requires them without assembly/disassembly tasks. Hence, the user does not need to assemble or disassemble modules.

b) Narrowing: to design the product family based on a common platform capable of integrating all functionalities required through separable modules. Each function is achieved by a particular module, and functions can be performed simultaneously or not depending on the functional requirements. This MAP facilitates the use of all required functionalities as long as the user requires them. Therefore, the designer can create assembly and disassembly modules to work with one, two or more functionalities simultaneously.

c) Component Swapping: to design the product family based on a common platform capable of receiving all functionalities through a common interface. This MAP entails the use of a single functionality at a time. The user can assemble and disassemble the particular required module when it is necessary.

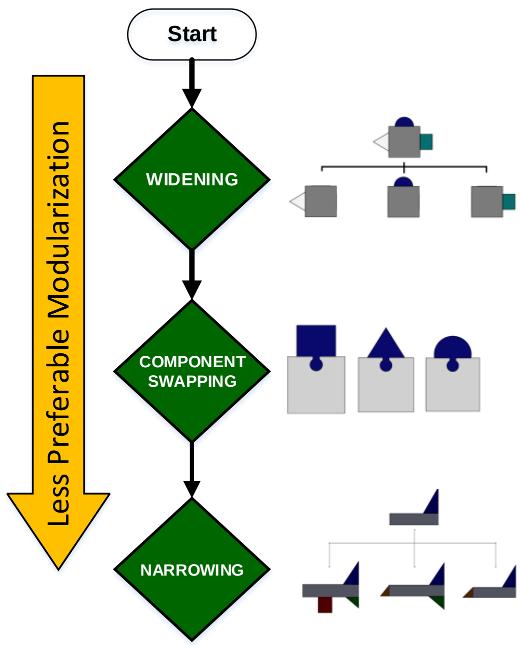


Figure 9. Hierarchy of Preferable MAPs for Functional Variation

3.5.2 Functional Range Hierarchy

MAPs for functional range are also classified in a preferable order according to functional requirements for product families based on growth paths. Figure 10 shows the flow diagram for the preferable selection of functional range MAPs in descending order. Also, design strategies for each MAP are described in detail below.

a) Component Sharing: To design modules to be shared in different PV. Such modules require being designed to cover all the operational ranges within the product family. The use of a single module for different PV entails the reduction of mass within the product family. However, such modules must be designed to satisfy higher reliability requirements due to longs cycles of use.

b) Adjustment: To design an adaptable module to cover operational ranges. Unlike the component sharing modules, the adaptable modules can involve adjustment task on the module to guarantee the desirable level of capability required. The adjustment can work in both continuous and discrete steps.

c) Stacking – Cut to Fit: To design modules to be separated in stacking (equal) or particular sections to satisfy different discrete levels. The use of stacking and cut to fit provides discrete adaptation through the use of common interfaces to increase or decrease the level or capability according to the functional requirements.

d) Size Range: to design modules in different sizes to satisfy each particular PV. This MAP is less preferable to others due to the need of a particular module for each product variant, unlike others functional range MAPs, which can share modules in different product variants or use a single module for all product variants (in the case of adjustment).

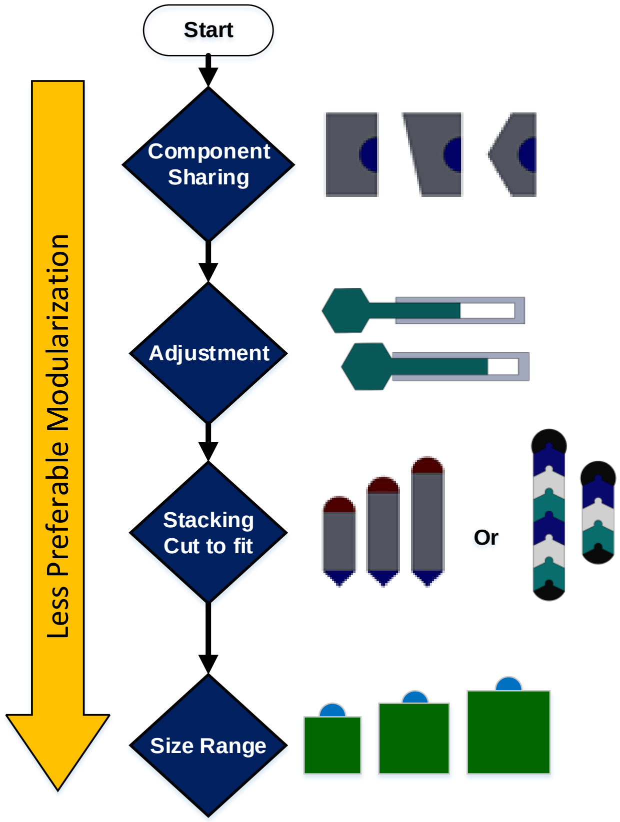


Figure 10. Hierarchy of Preferable MAPs for Functional Range

3.8 Identified Challenges

According to the sustainability analysis and the strategies mentioned, it is possible to identify the future challenges in the use of MAPs as strategy for the establishment of modular and OAP.

- The need of developing design methods for product interfaces and joints: the addition/removal of modules will be required not only during the manufacturing and final disposal but also in the use stage. The user must be able to upgrade and handle the module exchange, interfaces and joints need to be designed taking into account the minimum use of tools, standardised procedures and robustness.

- The need for policies of corporate sustainability responsibility since the lack of them difficult the integration of manufacturers, material producers, and final disposals companies. The establishment of effective supply chains between these lifecycle stages involves reduction of costs and better use of resources. The current separation of the companies participating in the product lifecycle generates an increase of new raw material processing, pollution due to products not sent to the final disposer, and emissions among others.

- Policies focused on educating users on sustainability and their responsibility during the use or operation stage. It is important to remark the awareness about reusability, the need to carry the product to the final disposal to continue with the cycle expected, and the importance of acquiring products from companies with sustainable supply chains from final disposal and material production. This challenge is one of the most significant to face. Sustainability education should be embedded in the learning culture from pre-K to higher education.

- The need for globally accepted metrics for sustainability: it is necessary to establish globally accepted metrics for assessing the lifecycle of modular products, taking into account the specific features involved in modularity (commonality of components, module sharing among others). Currently, it is very complex to develop the assessment of sustainability performance of products due to the variety of companies and the use of appropriate corporate indicators.

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Chapter 4

Methodological Contributions

Highlights

- An approach to design more sustainable Open Architecture Products is proposed based on modularity.
- Design phases proposed are described following a systematic information flow. Forms and tables are suggested to facilitate the design information management
- A set of indicators is proposed based on three main topics: conventional sustainability, circular economy and functional peformance

Contents

4.1 Introduction

Chapter 4 proposes a formal method for sustainable design of open architecture products based on modularity, which is remarked as one of the most relevant contributions of this thesis. Such design contributions are also based on CE strategies to enhance the overall sustainability performance of products without modifying their functionalities. Design tasks are added to the conventional product design process to minimize negative sustainability impacts and to entail reusability and recyclability of components. The methodology is proposed as a re-design process for existing products. Nonetheless, the design tasks described also provide a robust approach to evaluate and compare preliminary versions of new products.

Modularization algorithms are also proposed to modify components based on functional variety and Functional Range conditions explained in Chapter 3. All methodological steps are explained in detail using a systematic process guided by forms to ensure a comprehensive understanding of the proposed approach. Scope and limitations of the method are described as well. Further implementation and demonstration of the proposed approach are included in Chapter 5.

4.2 Methodological Contributions – Design Tasks

The proposed methodological approach to design sustainable OAP is based on the conventional four-stages design method established by Pahl et al., (Pahl et al., 1996), Pugh (Pugh, 1991), and Ullman (Ullman, 1992). The methodological contributions consist of ten design tasks included into the first three design phases (Task clarification, Conceptual design and Basic design). Design tasks include novel strategies related to the need of analysing the product family and identifying requirements regarding not only sustainability indicators but also circular economy (circularity) and functional aspects. Design tasks are characterised by the implementation of design topics such as analysis of product architecture, modularisation principles, and sustainability performance indicators within the product family. Figure 11 shows the ten design tasks proposed in each design phase.

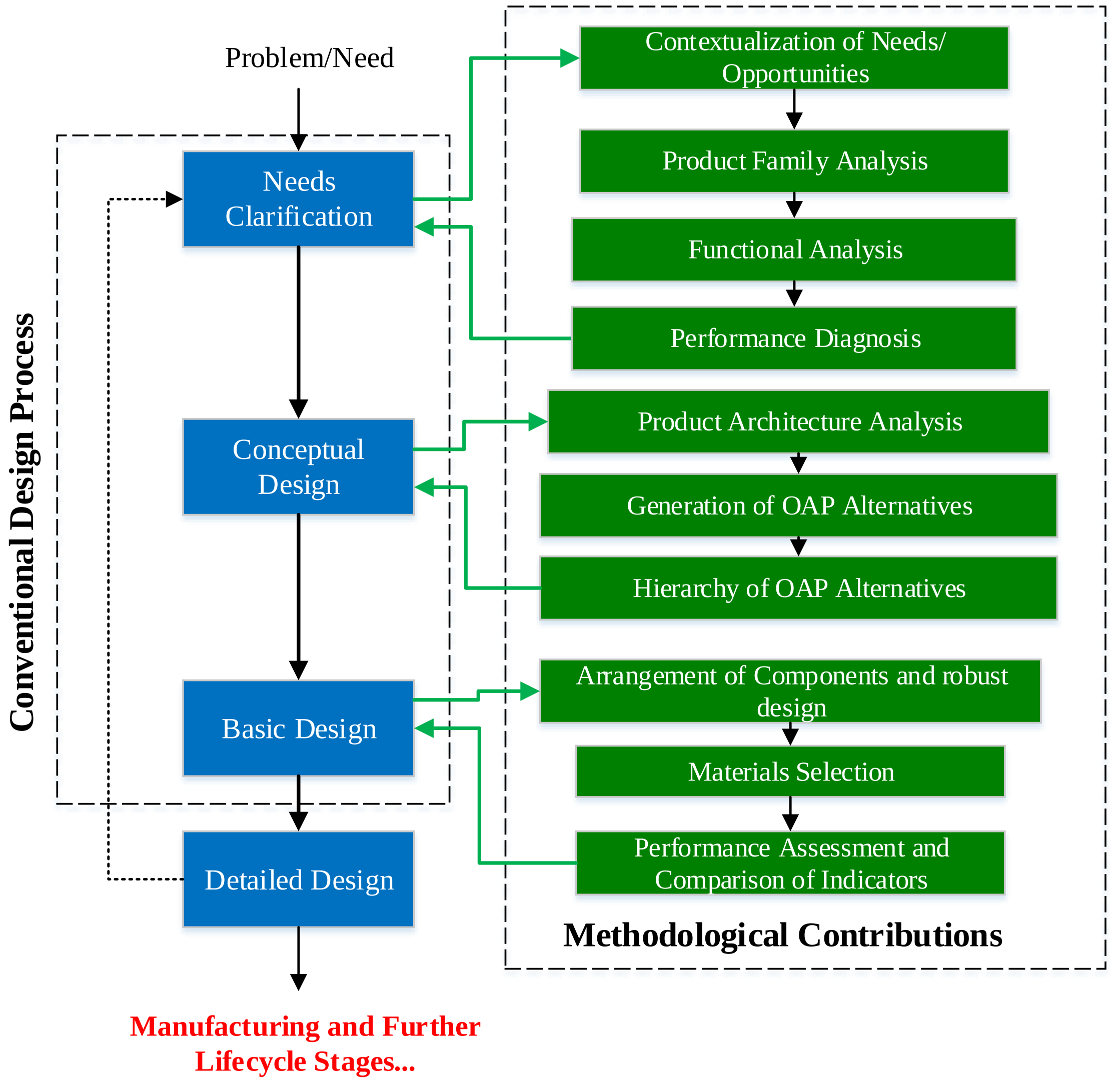

Figure 11. Methodological Contributions Proposed in the Design Process

The methodological contributions previously showed in Figure 11 are focused on task clarification, conceptual design and basic design stages. Most of researchers consider such stages as the most influential phases regarding impacts and the successful performance of products throughout the lifecycle of products.

Below, each methodological task is described in detail. Also, protocol forms are developed to manage the information (inputs and outputs) during all design process. It is important to clarify, the tasks proposed in this thesis are additional to conventional design procedures according to Pahl et al., (Pahl et al., 1996), Pugh (Pugh, 1991), and Ullman (Ullman, 1992). Therefore, only the proposed tasks are described in further subsections. The ten proposed tasks are only focused on Needs Clarification, Conceptual Design and Basic Design. Therefore, the Detailed Design step is not modified in the proposed methodology, and it comprises the traditional activities regarding detailed drawing and final specifications.

4.2.1 Needs Clarification Tasks

Involves the definition of needs and opportunities in terms of the product family specifications within the product family. Moreover, these design tasks lead to the designer towards the contextualization of needs, the product family analysis, the functional analysis and the performance diagnosis for the product family. All procedures comprised in this design phase are described as follows.

Contextualization of needs/opportunities: this first step aims to identify and describe the contextual situation related to the design needs and the identification of improvement opportunities for the product family. In this step, an analysis of market segments involved, problem magnitude and perspectives must be addressed. Regional context is also required as well as sustainability issues involved in the current product family lifecycle. Table 11 shows the form or matrix to summarise the contextualization of needs or improvement opportunities.

Table 11. Form for Contextualization of needs/opportunities

Description of Needs/ Opportunities	Market Segment	Regional Context	Current Sustainability Impacts Identified
Definition of problem situation, improvement opportunities, customer related issues[1]	Target market, special requirements.	Geographical context related to the problem. The impact can be regional or worldwide.	Sustainability impacts from the current product family according to indicators of interest.

Product Family Analysis: this task is comprised of the following summary of topics: a) Brief description of product functionalities. b) a representative CAD of the representative products within the product family. c) Identification of the type of variation parameters, which can be geometric (size, diameters, shape, scale) or related to performance (power, work, durability, resistance, capacity of load among others). d) Quantification of parameters involved in the variations identified. e) Number of Product Variant, and f) Nomenclature for the product variants within the product family. Table 12 represents the form for the analysis of Variation Parameters of the product family. Table 13 represents

[1] Clarification: text in grey represents data and information that need to be given by the designer concerning the particular design case

a form for the summary of PV and Table 14 denotes a form for the analysis of the number of pieces, which comprise the product family.

This design task aims to lead to the designer to identify and analyse the comprising product variants into the product family regarding the type and nature of the required variations throughout the product family. The engineering variation parameters must be identified in this design task for further analysis of the product family, considering the particular information of interest such as quantity of product variants, variety of components, number of pieces among others.

Table 12. Form for Variation Parameters of the Product Family

Brief description of product functionalities	CAD	Type of Variation parameters	Variation Parameters	Number of product Variants	Nomenclature
Function: Source of Variation: Existing Ranges Identified:	CAD or picture about product family	Geometry: _____ Performance: ____ Other: _____	Description of variation parameters	-	Identifier for PV1 Identifier for PV2 … Identifier for PVm

Table 13. Form for the Summary of Product Variants

PV(Product Variant) within the Product Family			
PV1	**PV2**	**…**	**PVm**
CAD PV1	CAD PV2	…	CAD PVm

Table 14. Form for Summary of PV

Componen t	CAD	Quantity per product variant	Variety of Component	Number of pieces within the Product Family
1	CAD or picture for component 1	Q_1	V_1	Q_1*V_1
2	CAD or picture for component2	Q_2	V_2	Q_2*V_2
…..	….	…	…	…
n	CAD or picture for component n	Q_k	V_k	Q_k*V_k

In addition to Tables 12,13 and 14, it is possible to generate an additional table to analyse the relationship Component-PV for the product family. Such table must indicate whether each component is related to any PV within the product family (see Table 15).

Table 15. Relationship Component – Product Variant for the prosthetic hand family

Component	Product Variant			
	PV1	PV2	…	PVm
1	1	…	…	…
2	-	1	…	…
…	…	…	…	…
n	…	…	…	…

Conventions
1: the component is included in the PV
-: the component is not included in the PV

Functional Analysis: this design task aims to identify the relative importance of each component within the product family, analysing the functionalities and assembly relationships involved respect to all PV. To accomplish this task, two main subtasks are necessary: a) to identify the number of functionalities involved in each component and b) to determine the relative functional importance of all components. The first subtask can be easily completed through a functional analysis of the products, which comprise the product family. On the other hand, the second subtask can be completed as indicates the Table 16. The Relative Functional Importance denotes the influence of the component within the product, modularisation of components with high Relative Functional Importance can represent major design interventions due to the number of functionalities and assembly relationships involved.

Table 16. Form for analysis of relative functional importance of components

Component	Number of Functions (F)	Number of components in contact with the assembly (N)	Number of components k	F*N/k	Relative Functional Importance
1	F_1	N_1	k_1	$F_1 * N_1 / k_1$	$F_1 * N_1 / (T^* k_1)$
2	F_2	N_2	k_2	$F_2 * N_2 / k_2$	$F_2 * N_2 / (T^* k_2)$
…	…	…	…	…	
n	F_n	N_n	k_n	$F_n * N_n / k_n$	$F_n * N_n / (T^* k_n)$
TOTAL (T)				$T = \sum_{i=1}^{n} F_i * N_i / k_i$	100%

Performance Diagnosis: this task consists of listing the measurements of indicators proposed to measure the sustainability performance of the product family. According to the summary of pieces and the mass of material involved, it is possible to estimate numerical values for each indicator. The set of sustainability indicators is comprised of conventional sustainability indicators and two new sets of parameters oriented to OAP (circularity and functional performance indicators). Table 17 shows the list of indicators to measure the sustainability performance of the product family.

Table 17. List of Sustainability Indicators: Conventional, Circularity and Functional Performance Indicators

Conventional Indicators	Proposed Indicators for OAP

	Circularity Performance indicators	Functional Performance Indicators
▪ Mass consumption ▪ Energy consumption ▪ Costs* ▪ CO_2 Footprint ▪ Health Risks Exposure	▪ Potential Reuse Index (RuI) ▪ Potential Recycle Index (ReI) ▪ Linear Flow Index (LFI)	▪ Reconfiguration Index (RI) ▪ Functional Variety Index (FV) ▪ Functional Range Index (FR)

*Cost related only to manufacturing

Each set of indicators is described in detail below:

Conventional Sustainability Indicators: these indicators are commonly employed to measure sustainability in product development processes. Each indicator is defined in detail below.

- **Mass Consumption (kg):** defined as the mass of manufacturing employed to manufacture the whole product family. From the perspective of sustainability, mass consumption is one of the most important parameters, due to its directly proportional relationship with another parameter such as energy consumption, Cost, and CO_2 Footprint. Those parameters increase proportionally as more mass is consumed to manufacture the product family. Also, this parameter is directly related to the weight of product variants within the product family.

- **Energy Consumption (MJ):** denotes the amount of energy consumed through the whole lifecycle of the product family. This parameter takes into account the energy required during primary material processing, manufacturing processing and recycling. To guarantee a most sustainable product family is required to reduce the value of this parameter.

- Cost **(USD)**: in this work, this parameter is related solely to the manufacturing cost of the product family. Therefore, consider the write-off time, overhead rate, manufacturing time and unitary material costs. Cost is modelled using a cost model based on Ashby (Ashby , 2000)[2]. Such model is described as follows (see Eq. 1):

$$Manuf.Cost \; = m * C_m + T\left(\frac{C_c}{t_{wo}} + C_{oh}\right) \qquad \text{Eq. 1}$$

Where:

m: mass of the product or component (kg)

2

Ashby , M. F., 2000. *Materials Selection in Mechanical Design.* 4th ed. Butterworth Heinemann.

C_m: Material Cost (USD per kg)

T: Manufacturing Time (hours)

C_c: Capital cost (USD)

t_{wo}: write-off time (hours)

C_{oh}: Overhead rate (USD per hour)

- **CO_2 Footprint (kg of CO_2):** the equivalent amount of CO_2 generated during the material processing, manufacturing and recycling of the mass of the product family. Concerning sustainability, the CO_2 footprint is one of the most widely employed indicators, referring to the total amount of greenhouse emissions generated during the lifecycle of any product, system, people or individual.

- **Health Risks Exposure:** this parameter is measured in a qualitative scale (Very Low to Very High) and denotes the health risk due to the exposure to the manufacturing material. Values of this parameter are obtained from engineering parameters such as flammability, the content of hazardous substances and chemical risks associated with the material. Annex I describes the scale proposed for this parameter.

Proposed Indicators for OAP: include Circularity and Functionality performance indicators. Such indicators aim to measure two main aspects: a) from the perspective of circular economy, the potential of products to be reused, recycled and the analysis of the material flow and b) the relative functional performance regarding the variety of components that provide enhancements over sustainability.

Circularity Performance Indicators: these indicators are related to the grade of circularity of the product family regarding reuse, recycle and circular flow. The set of circularity performance indicators is comprised of two new suggested indicators (Potential Reuse Index and Potential Recycle Index) and the Linear Flow Index established by (Ellen McArthur Foundation, 2010).

- **Potential Reuse Index (R_{UI}):** measures the proportion of mass, which provides reusability among the product variants within the product family. Is calculated as follows (See Eq. 2).

$$R_{UI} = \frac{M_R}{M_T} \qquad \text{Eq. 2}$$

Where M_R is the total amount of reusable mass and M_T is the total amount of mass which comprises the product family. The term "potential" denotes the ability of reuse. However, it is necessary to involve the user to guarantee the actual reusability of used components instead of employing new components.

- **Potential Recycle Index (*R_{EI}*):** this parameter represents the proportion of the mass of the product family which provide recycling processes. R_{EI} is calculated as follow (see Eq. 3).

$$R_{EI} = \frac{\sum(E_i * M_i)}{M_T} \qquad \text{Eq. 3}$$

Where E_i is the efficiency of recycling for the i_{th} component, M_i is the mass of component *i* and M_T is the total amount of mass of the product family.

- **Linear Flow Index (*LFI*):** measures the proportion of material (mass) flowing in a linear path considering from virgin materials and ending up as unrecoverable waste (Ellen McArthur Foundation, 2010). This index varies from 0 to 1, where 1 is a completely linear flow and 0 a completely restorative flow. Equation 4 describes the calculation of *LFI*.

$$LFI = \frac{V + W_u}{2M_T + \frac{W_f - W_r}{2}} \qquad \text{Eq. 4}$$

Where *V* is the mass of virgin feedstock in the product family, W_u is the mass of unrecoverable waste in the product family manufacturing, W_f is the mass of unrecoverable waste generated to produce recycled feedstock and W_r is the mass of unrecoverable waste generated during recycling.

Functional Performance Indicators: these indicators are suggested to assess the functionality changes in the product family respect the complexity provided by each design. Three indicators are defined to measure the ability of reconfiguration, the functionality variety and the operational range coverage offered by the product family. The modularisation of components implies changes in functional attributes. Therefore the values for these three indicators must remain the same or higher.

- **Reconfiguration Index (*RI*):** describes the relationship between the number of possible reconfigurations and the complexity of the product family. Equation 5 shows the calculation of *RI*.

$$LFI = \frac{R * P}{n} \qquad \text{Eq. 5}$$

Where R is the number of configurations in the product family, P is the number of product variants within the product family and n is the number of pieces in the whole product family.

- **Functional Range Index (*FR*):** this parameter denotes the relationship between the operational range or size provided by the product family respect its complexity. Therefore, a higher Functional Range Index is highly desirable when a modularisation process is conducted into a product family. On the other hand, the complexity reduction is desirable as well, since the same operational range is provided using fewer components. Calculation for *FR* is shown in Equation 6 below.

$$FR = \frac{C_1}{C_v} \qquad \text{Eq. 6}$$

Where C_1 is the number of component varieties capable of working in an operational range and C_v is the total component variety within the product family.

- **Functional Variety Index (*FV*):** measures the relationship between the number of functionalities and the complexity of the product family. It is desirable to increase this indicator, which means the OAP product family is capable of offering more functionalities for a particular complexity and the complexity of the product family has been reduced. Equation 7 shows the calculation for the *FV* indicator.

$$FV = \frac{C_2}{C_v} \qquad \text{Eq. 7}$$

Where C_2 is the number of component varieties that offer more than one functionality, and C_v is the total component variety within the product family.

The set of indicators mentioned above in Table 17 will be compared to the open architecture design obtained once the proposed design methodology is applied. Therefore, values obtained in the sustainability diagnosis task need to be saved at the comparison stage.

4.2.2 Conceptual Design

This design stage involves the analysis of product architecture and the generation of modular alternatives to satisfy the contextual requirements and to develop suitable preliminary design alternatives.

Product Architecture Analysis: this step involves the definition of possible Modular Architecture Principles – MAPs applicable to each constructive component within the product family. Two main subtasks are developed in this phase: a) the identification of Functional Range and Functional Variety and requirements into the product family, and b) the definition of applicable MAPs for components. The first subtask can be achieved checking all constructive components concerning the performing of different functionalities and several operational levels within the product family. Table 18 is proposed as a summarised form to consolidate this subtask. Such Table also provides blanks to summarise a brief description of the Functional Range and Functional Variety condition identified for each component.

Table 18. Functional Range and Functional Variety Identification for the family of prosthetic hands

Component	Functional Variety Identification		Functional Range Identification	
	FV	Description	FR	Description
1	Y/N	-	Y/N	-
2	Y/N	-	Y/N	-
…	…	-	…	-
n	Y/N	-	Y/N	-

The definition of applicable MAPs is established through two decision algorithms based on the type of modularisation required, which can be oriented to increase the number of functionalities available (functional variety) or to increase the operational product capacity (functional level). Such algorithms are based on a set of sequential questions about functional requirements of each component to provide particular MAPs consideration. It is important to clarify that the implementation of MAPs should be suitable to modify the geometry of any component. Otherwise, the product component remains unmodifiable according to the original product design or initial product version. Figure 12 and Figure 13 show the decision process for both, functional variety and functional level.

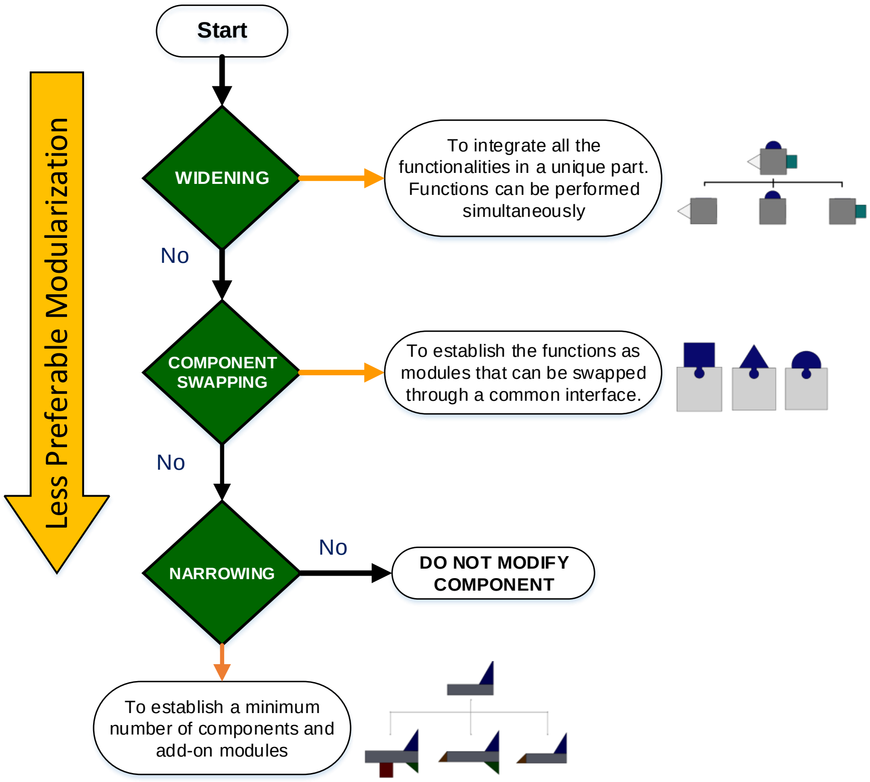

Figure 12. Decision Algorithm for Functional Variety

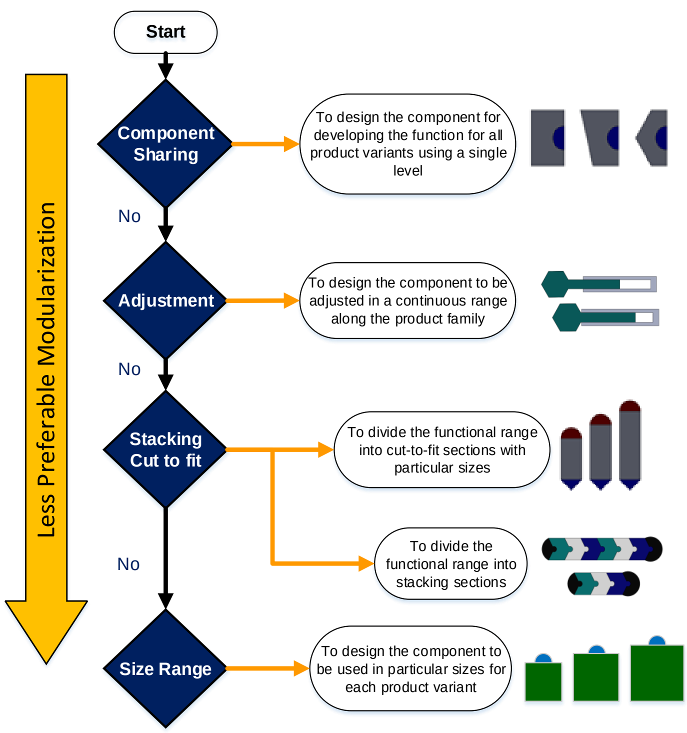

Figure 13. Decision Algorithm for Functional Range

Table 19. Form for description of Functional Variety and Functional Range Modularization

Component	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	constraints	Suitable
Name component1	MAP 1	Modifications for component 1 using MAP1	Constraints identified	Yes/No
	MAP2	Modifications for component 1 using MAP2	Constraints identified	Yes/No
	…	…	…	
	MAPn	Modifications for component 1 using MAPn	Constraints identified	Yes/No

Generation of OAP Alternatives: this task comprises the conceptual generation of geometrical modifications for modularising each component according to the implementation of algorithms previously showed. The number of possible alternatives depends on the complexity of each component and how susceptible is such component to be modified through the implementation of any MAP. It is important to clarify that MAPs are established in a preferable order according to their advantages concerning sustainability. However, it is possible that more than one MAP can be implemented. To complete this task, Table 20 is proposed to describe detail the geometrical modifications involved in the modularisation of components.

Table 20. Form for describe component modularisation

<table>
<tr><th>Component 1</th><th>Implemented MAP</th></tr>
<tr><td rowspan="2">Conceptual Drawing or CAD about the proposed modification</td><td>Implemented Principle</td></tr>
<tr><td>Sustainability Benefits: benefits of the modification are summarised here.</td></tr>
<tr><td colspan="2">Description: description of modification must be described here.</td></tr>
</table>

Hierarchy of OAP Alternatives: once the conceptual modularisation of components is generated according to the modularisation algorithms proposed, it is possible that one component can be modularised using more than one MAP. Therefore, in that case, it is necessary to compare and rank the alternatives. To determine a suitable hierarchy of OAP alternatives, Table 21 shows a complexity-based decision process. Which considers two main parameters, the Pugh Complexity (*CI*) from Pugh (Pugh, 1996), and the Assembly Disassembly Complexity Index (C_{TM}) from Mesa et al. (Mesa et al., 2017). The decision parameter is calculated as the square root of the multiplication between *CI* and C_{TM}, the alternative with lower value is established as the most suitable. Calculation of both parameters is described in detail in Annex II.

It is important to clarify that the selection process for the best alternative can also be so addressed using weighted weights, Analytical Hierarchical Process – AHP or any decision approaching using additional decision parameters. The hierarchy process proposed in this work is based on the complexity due to the number of components and assembly/disassembly relationships within the product family.

Table 21. Form for technical comparison between modularisation alternatives

OAP Alternatives	Summary of components for PV	Overall Pugh Complexity Index (CI)	Overall Assembly-Disassembly Complexity Index (C_{TM})	$\sqrt{CI * C_{TM}}$
Alternative 1	…	CI_1	C_{TM1}	$\sqrt{CI_1 * C_{TM1}}$
Alternative 2	…	CI_2	C_{TM2}	$\sqrt{CI_2 * C_{TM2}}$
…	…	…	…	…
Alternative n	…	CI_n	C_{TMn}	$\sqrt{CI_n * C_{TMn}}$

4.2.3 Basic Design

Design task in this stage aims to define the definitive geometry and materials for each constructive component or module in the product family. The definition of sizes, interfaces design and materials selection. Besides, the last step is included regarding the measurement of indicators mentioned in Table 17 and a comprehensive comparison between the initial product family and the OAP family regarding sustainability performance indicators.

Arrangement of components and robust design: this task consists of the detailed definition of dimensions and parametrisation according to the conceptual modularisation developed in the previous design stage. Tolerance, fittings and interface suitability must be considered in this task. Possibly conceptual modifications can be required during this stage. Therefore, the iteration between conceptual and basic design is critical. In this design phase is highly recommendable to employ CAD models to describe the final modifications achieved.

Materials Selection: involves the definition of most suitable manufacturing material for each component within the product family according to the durability requirements of the product and the sustainability performance associated with the material. The material selection is comprised of two phases:

a) Establishment of Manufacturing Scenarios: which includes the alternatives of materials to manufacture the product family. Such scenarios can also include more than one material due to the durability requirements. Components with high durability requirements can be manufactured using the most durable material, while components with low durability requirements can be manufactured using a material with lower durability performance.

   Durability is measured using environmental and mechanical aspects. The proposed scale to measure environmental durability is summarised in Annex III. On the other hand, mechanical durability is calculated as the square root of the multiplication between the tensile strength and the fatigue resistance at 10^7 cycles for the same material. For instance, the mechanical durability for PLA (Polylactic Acid) is calculated as the square root of the result from multiplying 54MPa (average tensile strength) and 16MPa (average fatigue resistance at 10^7 cycles), as result the value obtained is 29.4. A graphical comparison between manufacturing materials is highly recommended to determine the most suitable manufacturing alternative. Depending on the regional context and requirements, the mechanical and environmental durability desired must be established and compared to the manufacturing scenarios.

Performance assessment and comparison of Indicators: Sustainability performance indicators measured in the Clarification of needs and opportunities phase must be re-calculated for the new design obtained from the proposed methodological contributions. A graphical comparison should be developed to facilitate the analysis of results. Also, percentual changes can be summarised to demonstrate the influence of the methodology over the sustainability indicators. It is important to clarify that iterations between conceptual and basic design should be addressed to ensure suitable results, a multi-disciplinary analysis is highly recommended based on the nature of the product family.

4.3 Scope and limitations

The methodological contributions proposed are based on the traditional four-stage design method. Ten methodological contributions are described in detail in this chapter. The scope and limitations regarding the proposed approach are listed in detail below:

Scope:

The methodological contributions aim to increase the performance of product families regarding sustainability, circularity and functionality. The modularisation of product families to generate OAP families facilitates the sharing of components and the reduction of components which can be useful in different product variants.

Limitations:

- The proposed approach is limited to product families which involve a progressive change in operational levels of use. Therefore, products need to be replaced in short useful life cycles (In-Series Use). However, can be implemented in product families for In-parallel use.

- Indicators to measure sustainability performance are established as generic indicators. Additional indicators can be added if the case study requires it.

- Modularization modifications can be easily implemented in components with low complexity and assembly relationships. In the case of modularisation of critical components (high importance within the product variant) is required to develop major modifications which involve radical alterations on the component. The proposed approach is focused to modularise based on minor modifications that do not alter the main functionalities of the component.

- Proposed design contributions are solely focused on reuse and recycling considerations. The remanufacturing scenario and reparability tasks are not considered in the design contributions proposed. Therefore, components must be designed to be repaired in case of a common failure through easy disassembly operations to facilitate the replacement of damaged components.

To summarise the proposed design contributions from a holistic perspective, Table 22 list the inputs, outputs and relevance for the ten design tasks proposed in this work.

Table 22. Description of Inputs, outputs and relevance of each proposed task

Proposed Task	Inputs	Outputs	Relevance
Needs Contextualization	Information about economic, social, cultural context related to needs and opportunities	Summary of extra-requirements and additional design considerations	Increase of the robustness in the design process and overall positive impact for users
Product Family Analysis	Summary of the product family, constructive components.	Measurement of product family complexity and existing functional variations	Understanding of product component relationships and variation parameters

Proposed Task	Inputs	Outputs	Relevance
Performance Diagnosis	Values of current parameters related to sustainability performance indicators	Valuation of current sustainability and functional performance	Establishment of reference basis for improving overall product family performance
Product Architecture Analysis	Functionalities and operational ranges of each module or component	Suitable modular architecture principles to satisfy the required functional variety for each module or component	Definition of modularised particular alternatives for each component
Generation of OAP Alternatives	Modular alternatives for components	Sketches of Modularized design alternatives for components	Definition of Modularized conceptual design alternatives and geometrical modifications
Hierarchy of OAP Alternatives	Set of modular alternatives for the same component	Hierarchy of Modularization alternatives	Definition of hierarchy to select the most suitable modularisation alternative
Component Arrangement and Robust Design	Sketches of Modularized design alternatives for components	Definitive geometry for each product variant into the product family	Verification of geometric compatibility among modules and product variants
Materials Selection	Alternatives for Manufacturing materials (Manufacturing scenarios)	Manufacturing material assessment regarding sustainability	Provide useful information for the decision making in the selection of material for each module or component
Assessment and Comparison of Indicators	Values of new parameters related to sustainability performance indicators	Comparison of sustainability performance indicators	Establishment of Improvements and the evolution of indicators for the new design

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Chapter 5

Case Study: Re-design of a Family of prosthetic hand devices for children

Highlights

- The proposed method described in the previous chapter is implemented on a family of prosthetic devices for children (case study).
- A demostration of the information flows is performed using real information from the case study.
- Comparision of indicators is presented to validate the effectiveness of the proposed method.

Contents

5.1 Introduction

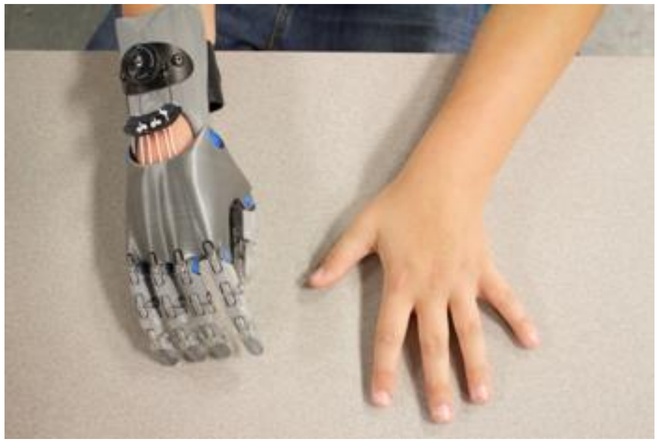
This chapter comprises the implementation of the methodological contributions of a product family of prosthetic devices. The methodological steps described in Chapter 4 are followed systematically through the design process, providing useful information for the decision-making in the selection of modularisation alternatives for each component. This chapter includes a description of the case study considered, followed by the methodological contributions proposed during the Task Clarification, Conceptual Design and Basic Design phases. Graphical aids are used to provide a better comprehension concerning sustainability performance indicators. This chapter is limited to the implementation of the method. Therefore, analysis of results and discussion are included in Chapter 6.

5.2 Description of the Case Study

The case study consists of the redesign of a 3D-printed prosthetic hand named "Cyborg Beast". This device is designed for patients with ages between 4 and 12 years with congenital partial hand reductions or acquired partial hand amputations. The overall function of the Cyborg Beast device is to emulate partially the hand functionality, providing a similar anthropometric shape and range of motion compared to a human hand. Cyborg Beast is conceived as a low-cost alternative for children with upper-limb reductions, especially for regions where insurance and public health funding are insufficient and the families' financial resources are limited (Zuñiga et al., 2015). Figure 14 shows three pictures of the Cyborg Beast device for a left-handed patient.

a)

b)



c)

Figure 14. Cyborg Beast Device (Right Hand)

Cyborg Beast is designed as a body-powered device, which provides passive finger extension and active flexion using only the patient's wrist movement. Passive finger extension is achieved through elastic cords placed inside dorsal aspect of the fingers. Finger flexion is performed by non-elastic cords along the palmar surface of each finger and is driven by 20-30 degrees of wrist flexion. (Zuniga, et al., 2017).

For the analysis of the case study, four sizes of Cyborg Beast (100%, 110%, 120% and 130%) are chosen for both, right hand and left-hand patients. Such sizes correspond to children between 4 and 12 years of age. Hence, the product family analysis is comprised of eight Product Variants (PV).

5.3 Implementation of Design Tasks[3]

The methodology previously proposed in Chapter 4 is developed on the case study aforementioned, following the ten methodological contributions established along the design phases. The method aims to improve sustainability performance minimizing detriments in function. The development of each design task on the case study is described in detail as follows.

5.3.1 Needs Clarification Tasks

5.3.1.1 Contextualization of needs/opportunities

The current prosthetic hand family analysis is focused on the functionalities provided to children and the social impact associated with its use. In addition, the market segment and regional context are

[3] green text in all tables and forms represents data and information concerning the case study previously described.

identified, and the current sustainability impacts are established as well. The high costs for prosthetic devices and the requirement of several device sizes during the growth of children are identified as opportunities for improvement. The market segment for the case study is comprised of patients with ages between four and12 years for both, male and female children. Regional context encompasses two main aspects: a) the existing population of children with congenital partial hand reductions around the world (1 in 90.000 births) (Nair et al., 2011) and b) the number of children with finger amputations due to armed conflict and accidents. Table 23 shows the aspects regarding the needs contextualization task.

It is possible to identify the following issues as key sustainability impacts:

a) The need of changing due to the natural limb growth entails short useful lives for each prosthetic hand size, and the generation of waste due to full discarded products. (See Figure 15).
b) None of the components is designed to be reusable in more than one size within the product family for the current design.

Table 23. Contextualization of needs/opportunities for prosthetic hands family

Description of Problem / Opportunities	Market Segment	Regional Context	Current Sustainability Impacts Identified
Amputee children require several prosthetic devices due to natural limb growth.	Children from 4 to 12 years old. Male and Female. Left and Right Hand.	Children around the world with congenital partial hand reduction deficiencies (Ectrodactyly).	Waste generation due to the need for several product variants according to the natural limb growth.
High costs for prosthetic devices.		Children with upper limb reductions around the word victims of accidents or armed conflict.	Short useful times for prosthetic devices.
Prominent advances in additive manufacturing (3D Printing).			None of the constructive components can be reused when the prosthetic hand size is changed.

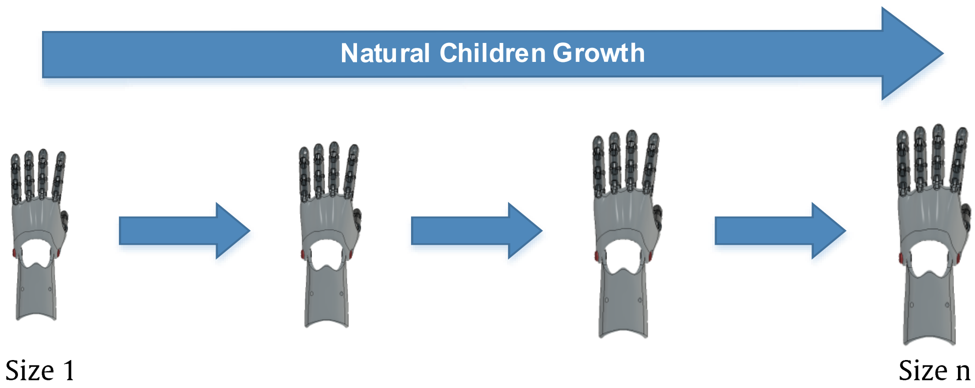


Figure 15. Sequence of Prosthetic Devices required based on Natural Children Growth

5.3.1.2 Product Family Analysis

Firstly, the prosthetic hand sizes (100%, 110%, 120% and 130%) are analysed to identify the product functionalities, the type of variation parameters as well as its values, the number of product variants and chosen nomenclature for product variants. Table 24 summarises the Product Family Analysis task for the case study.

Secondly, the PVs are differentiated according to the information consolidated in Table 24 and a summary of constructive components of the product family. To illustrate this in an elucidated manner, Table 25 and Table 26 are proposed to show the eight PVs within the product family and the comprising constructive components of it respectively.

Table 24. Identification of Variation Parameters for the case study

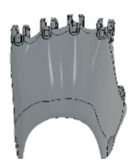
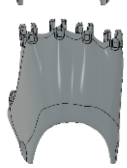
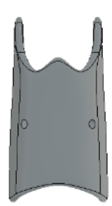
Brief description of product functionalities	CAD	Type of Variation parameters	Variation Parameters	Number of Product Variants	Nomenclature
Function: Handgrip **Source of Variation:** Children's arm size growth **Working Range:** 100%-130%		**Geometry:** Full Geometrical Scaling **Others:** Handgrip for Right-hand Handgrip for Left-hand	Length Height Width Working Hand	8	Right-hand PV1-PV4 (100%-110%-120%-130%) Left-hand PV5-PV8 (100%-110%-120%-130%)

Finally, Table 27 shows the component variety relationship across all the eight PVs considered in the product family. The left and right palms are used exclusively by one PV. Meanwhile, the rest of components are used by two PVs. In the case of fingers, thumbs, gauntlet, finger pin, wrist pin and wrist ring, they are employed in two PVs due to their functionality does not depend on the type of hand (right or left).

Table 25. Summary of PVs

Product Variants (PVs) within the product family				
	100%	110%	120%	130%
Left Hand				
	PV1	PV2	PV3	PV4
Right-Hand				
	PV5	PV6	PV7	PV8

Table 26. Summary of constructive components for the prosthetic hand family

Component	CAD	Quantity per PV	Variety of componen t	Number of components within the Product Family
Left Palm		1	4	4
Right Palm		1	4	4
Gauntlet		1	4	8

Component	CAD	Quantity per PV	Variety of componen t	Number of components within the Product Family
Finger		4	4	32
Thumb		1	4	8
Finger Pin		5	4	40
Wrist Pin		2	4	16
Wrist Ring		2	4	16
TOTAL				128

Table 27. Component – Product Variant Relationship for the prosthetic hand family

Component Variety	Product Variant PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8
Right Palm$_1$	1	-	-	-	-	-	-	-
Right Palm$_2$	-	1	-	-	-	-	-	-
Right Palm$_3$	-	-	1	-	-	-	-	-
Right Palm$_4$	-	-	-	1	-	-	-	-
Left Palm$_1$	-	-	-	-	1	-	-	-
Left Palm$_2$	-	-	-	-	-	1	-	-
Left Palm$_3$	-	-	-	-	-	-	1	-
Left Palm$_4$	-	-	-	-	-	-	-	1
Gauntlet$_1$	1	-	-	-	1	-	-	-
Gauntlet$_2$	-	1	-	-	-	1	-	-
Gauntlet$_3$	-	-	1	-	-	-	1	-
Gauntlet$_4$	-	-	-	1	-	-	-	1
Finger$_1$	1	-	-	-	1	-	-	-
Finger$_2$	-	1	-	-	-	1	-	-
Finger$_3$	-	-	1	-	-	-	1	-
Finger$_4$	-	-	-	1	-	-	-	1
Thumb$_1$	1	-	-	-	1	-	-	-
Thumb$_2$	-	1	-	-	-	1	-	-
Thumb$_3$	-	-	1	-	-	-	1	-
Thumb$_4$	-	-	-	1	-	-	-	1
Finger Pin$_1$	1	-	-	-	1	-	-	-
Finger Pin$_2$	-	1	-	-	-	1	-	-
Finger Pin$_3$	-	-	1	-	-	-	1	-
Finger Pin$_4$	-	-	-	1	-	-	-	1
Wrist Pin$_1$	1	-	-	-	1	-	-	-
Wrist Pin$_2$	-	1	-	-	-	1	-	-
Wrist Pin$_3$	-	-	1	-	-	-	1	-
Wrist Pin$_4$	-	-	-	1	-	-	-	1
Wrist Ring$_1$	1	-	-	-	1	-	-	-
Wrist Ring$_2$	-	1	-	-	-	1	-	-
Wrist Ring$_3$	-	-	1	-	-	-	1	-
Wrist Ring$_4$	-	-	-	1	-	-	-	1

5.3.1.3 Functional Analysis

The functional analysis for the prosthetic hand family is developed according to the steps proposed in chapter 4. Figure 16 shows the functional structure of the prosthetic hand. The number of functionalities of each component and the number of components in contact within the assembly of the product are calculated to measure the relative functional importance. In this case, the most important component is the palm (62.5%), followed by the gauntlet (13.9%) and the wrist pin (8.3%). Table 28 shows the calculation of the relative functional importance of the case study.

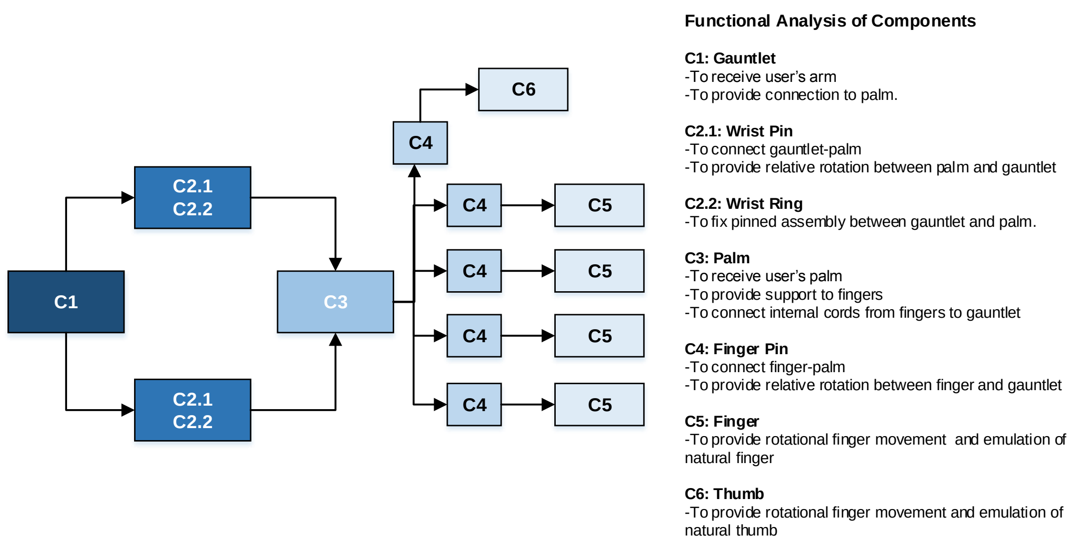


Figure 16. Functional Analysis of constructive components for the prosthetic hand

Table 28. Relative Functional Importance of components within the prosthetic hand

Component	Number of Functions (F)	Number of components in contact with the assembly (N)	Number of components n	F*N/n	Relative Functional Importance
C1: Gauntlet	2	5	1	10	13.9%
C2.1: Wrist Pin	2	6	2	6	8.3%
C2.2: Wrist Ring	1	6	2	3	4.2%
C3: Palm	3	15	1	45	62.5%
C4: Finger Pin	2	10	5	4	5.5%
C5: Finger	1	8	4	2	2.8%
C6:Thumb	1	2	1	2	2.8%
TOTAL				72	100%

5.3.1.4 Performance Diagnosis

The Performance Diagnosis task is developed assessing the three main performances proposed in section 4. This task is comprised of a) the conventional sustainability indicators, related to the conventional environmental, economic and social indicators; b) the circularity indicators which measures the ability of the product family to be reused, recycled in a circular path and finally; and c) the Functional Indicators, associated with the functionalities provided by the product family.

Conventional Indicators measurement: this is measured from the total mass of the product family involved in the whole lifecycle. In this case, the masses are obtained from the 3D printing software (Ultimaker Cura), which can predict accurately the mass of material required in the manufacturing process. Table 29 summarises the mass for each PV within the product family. Once the mass is measured, the energy consumption and CO_2 footprint are calculated through the relative values obtained from the CES Selector® Software. Table 30 shows the values of the conventional sustainability indicators for the family of product hands. Annex IV summarises the origin of values showed in Tables 29 and 30.

Table 29. Masses of the family of prosthetic hands

Product Variant	Size	Mass (kg)
PV_1	100%	0.1589
PV_2	110%	0.2040
PV_3	120%	0.2560
PV_4	130%	0.3162
PV_5	100%	0.1589
PV_6	110%	0.2040
PV_7	120%	0.2560
PV_8	130%	0.3162
TOTAL		1.8705

Table 30. Values of conventional sustainability indicators for the family of prosthetic hands

Conventional Sustainability Indicators	Units	Values for original design
Mass Consumption	kg	1.8705
Energy Consumption*	MJ	140.48
CO_2 footprint*	kg	9.91×10^{-3}
Manufacturing Cost	USD	1119.6
Health Risk Exposition**	-	High

*Includes primary production, manufacturing and recycling
**Based on ROHS and Flammability

Circularity Indicators: the circularity is measured using three main indicators: a) Potential Reuse Index, b) Potential Recycle Index, and c) Linear flow index. The calculation of indicators mentioned above is developed using the values of the total mass for the product family, recyclable mass, reusable mass, the mass of virgin feedstock, and mass of unrecoverable waste.

Functional Indicators: functional performance is measured from the number of functionalities, the operational ranges and product family complexity. Three main indicators are proposed to assess the functional performance: a) Reconfiguration Index, b) Functional Range Index, and c) Functional Variety Index.

Circularity and Functional calculation parameters are listed in Table 31,while Table 32 includes the values of Circularity and Functional indicators.

Table 31. Calculation parameters for Circularity and Functional Indicators

Calculation Parameters	Units	Values for Original Design
Total mass of the product family - Mt	kg	1.87
Total mass of reusable components - Mr	kg	0
Recycling Efficiency - Ei	-	0.9
Fraction of recyclable mass for i component Fi	-	1
Mass of virgin feedstock in the PF – V	kg	0.187
Mass of unrecoverable waste in PF manuf. - Wu	kg	0
Mass of unrecoverable waste generated to produce recycled feedstock - Wf	kg	0.187
Mass of unrecoverable waste generated during recycling - Wr	kg	0.187
Number of product variants P	-	8
Number of reconfigurations in the product family - R	-	0
Number of components in the PF – n	-	128
Component Variety within the product Family C_V	-	2
Number of component variety capable of working in an operational range C_1	-	0
Number of component Variety with more than one functionality C_2	-	0

Table 32. Calculated Indicators for Circularity and Functional Performance

Calculated Indicators	Values for Original Design
Circularity Indicators	
Potential Reuse Index - RuI	0
Potential Recycle Index - ReI	0.9
Linear Flow Index - LFI	0.048
Functional Indicators	
Reconfiguration Index - RI	0 (NA*)
Functional Range Index - FL	0 (NA*)
Functional Variety Index - FV	0 (NA*)

*NA: not existing values

5.3.2 Conceptual Design

5.3.2.1 Product Architecture Analysis

The Product Architecture Analysis task comprises in the first place the identification of functional Range and Functional Variety conditions for all the constructive components of the product family. For the case study, it is possible to identify that the palm component offers both, Functional Range and Variety within the product family. Meanwhile, the rest of components provide only Functional Range. Table 33 shows the functional Range and Functional Variety identification for the components that comprise the prosthetic hand.

Table 33. Functional Variety and Functional Range Identification for the family of prosthetic hands

Component	Functional Variety Identification		Functional Range Identification	
	FV	Description	FR	Description
Palm	Y	Left Hand and Right Hand	Y	Scaling from 100% to 130%
Gauntlet	N	-	Y	Scaling from 100% to 130%
Finger	N	-	Y	Scaling from 100% to 130%
Thumb	N	-	Y	Scaling from 100% to 130%
Finger Pin	N	-	Y	Scaling from 100% to 130%
Wrist Pin	N	-	Y	Scaling from 100% to 130%
Wrist Ring	N	-	Y	Scaling from 100% to 130%

Y: Yes N: No

The implementation of Functional Variety and Functional Range algorithms is performed in detail below, Figures 17 and 18 show the algorithm sequence for the component modularisation. Table 34 shows the Functional Variety analysis for the Palm. Furthermore, Tables 36 to 38 describe the Functional Range analysis for all components of the prosthetic device.

Functional Variety Analysis:

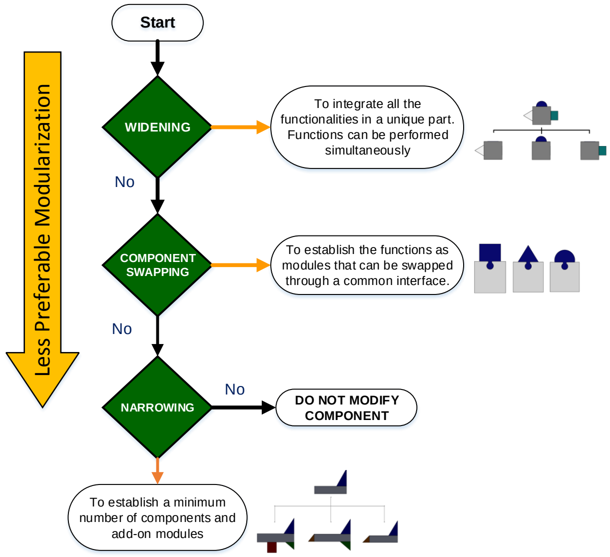


Figure 17. Modularization algorithm for Functional Variety

Table 34. Functional Variety Modularization for palm

Component	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	Comment	Suitable
Palm	Widening	To use a unique symmetric palm to satisfy both left and right hand. To design a six-finger hand with left and right thumbs. The palm requires one additional thumb interface.	Users do not need to use both thumbs simultaneously.	No
	Component Swapping	To swap left and right thumb through a common interface.	The thumb is symmetric. Therefore, the same thumb works on the right and left hand. A common interface does not provide left-handed and right-handed functionalities.	No
	Narrowing	To generate a symmetrical common palm capable of assembling both right and left thumb. The palm requires symmetrical thumb interface to guarantee equal functional performance for both, right and left hand.	The narrowing facilitates the manufacturing of the palm. Depending on the user, the palm can be adapted to the right or left hand.	**Yes**

Functional Range Analysis

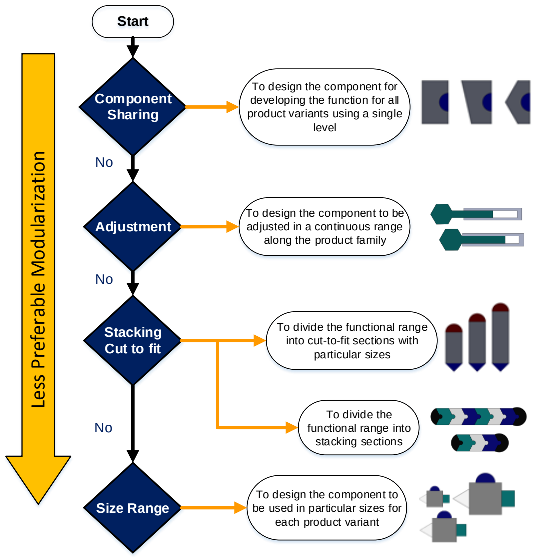


Figure 18. Modularization algorithm for Functional Range

Table 35. Functional Range Modularization for Palm

Component	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	Constraints	Suitable
Palm	Component Sharing	To use a unique palm to satisfy all product variants It requires standardization of joining holes	A single level cannot satisfy all product variants due to the socket growth and increase of the distance between joining points.	No
	Adjustment	To adjust a unique palm to satisfy all product variants incurs in the separation of palm sections. It involves additional joints.	Separation of palm incurs in compatibility problems due to internal conduit connections*	No
	Stacking	To separate palm into stackable sections It involves additional joints	Palm geometry does not allow the stacking of sections. *	No
	Cut to fit	Geometry shapes do not allow to stack particular palm sections It involves additional joints	Palm geometry does not allow the cut-to-fit sections. *	No
	Size Range (current)	-	-	Yes

*See Annex V

Table 36. Functional Range Modularization for Gauntlet

Functional Range	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	Constraints	Suitable
Gauntlet	Component Sharing	To use a unique gauntlet to satisfy all product variants It involves verification of joints between palm and gauntlet	A single level cannot satisfy all product variants due to the arm growth	No
	Adjustment	All gauntlet sizes can be constructed using common adjustable arc sections. It involves verification of joints between palm and gauntlet.	It requires establishing a joining method for adjustable arc sections	Yes
	Stacking	All gauntlet sizes can be constructed using stackable sections. It involves verification of joints between palm and gauntlet. In addition, additional joints between stacking sections.	It requires establishing a joining method for stackable sections	Yes
	Cut to fit	To establish particular gauntlet sections with common add-on modules. It involves additional joints	Add-on modules require different shapes due to the joining points for the four gauntlet sizes	No

Table 37. Functional Range Modularization for Fingers & Thumb

Functional Range	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	Constraints	Suitable
Fingers & Thumb	Component Sharing	To employ a unique size of fingers and thumb for all product variants, It requires standardisation of pinholes in joints.	It is necessary to use different finger and thumb sizes due to the child natural growth	No
	Adjustment	To use an adjustable finger for all product variants Fingers rotational joints need to be removed, adding additional connectors. Conduits need to be also verified.	Separation of fingers and thumb involves supplementary connectors and joining tasks. * Current rotational functionality and conduit alignment are affected	No
	Stacking	To generate stacking sections of fingers and thumb. It involves an increase of number of joints and connectors	Separation of fingers and thumb involves supplementary connectors and joining tasks. * Current rotational functionality and conduit alignment are affected	No
	Cut to fit	Geometry shapes do not allow stacking particular finger sections. It involves an increase of number of joints and connectors	Separation of fingers and thumb involves supplementary connectors and joining tasks. * Current rotational functionality and conduit alignment are affected	No
	Size Range (current)	-	-	Yes

*See Annex V

Table 38. Functional Range Modularization for Finger Pin, Wrist Pin and Wrist Ring

Functional Range	Possible Modularization Principle	Geometric and Assembly/Disassembly Modifications	Constraints	Suitable
Finger Pin	Component Sharing	To use a unique finger pin size for all product variant, It involves standardisation of joining holes among fingers-palm and thumb-palm subassemblies	To use a standard size requires the verification of stresses and strength of the along the product variants.	Yes
Wrist Pin	Component Sharing	To use a unique wrist pin size for all product variant. It involves standardisation of joining holes among gauntlet-palm subassemblies	To use a common size requires the verification of stresses and strength of the along the product variants.	Yes
Wrist Ring	Component Sharing	To use a unique wrist ring size for all product variant. It involves standardisation of joining holes among gauntlet-palm subassemblies	To use a common size requires the verification of stresses and strength of the along the product variants.	Yes

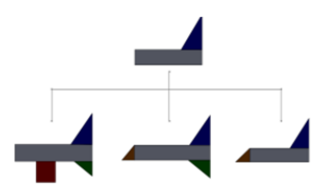
5.3.2.2 Generation of OAP Alternatives

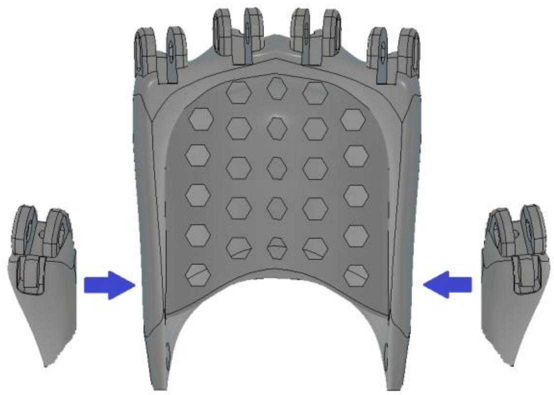
Geometrical modifications are described in detail below for both, Functional Variety and Functional Range conditions previously identified for the components of the prosthetic hand.

Functional Variety Modifications:

The component identified with Functional Variety condition is the palm, which offers both, right-handed and left-handed functionalities for PV_1 to PV_4 and PV_5-PV_8 respectively. In the case of the palm, the implementation of the modularisation algorithm for functional variety entails the Narrowing principle, which establishes the use of a common palm for both, right and left hand and the modularisation of the thumb assembly. Table 39 describes the palm modularisation proposed using the Narrowing principle.

Table 39. Palm modification – Thumb Modularization (Narrowing)

Palm - Modularized Thumb	Implemented MAP
	Narrowing 

	Sustainability Benefits: symmetric palms entail the reduction of components, four symmetric palms replace eight non-symmetric palms.
Description: The right and left thumb are modularised through an interface on a complete symmetric palm. Therefore, a unique palm can be employed as both, right or left hand.	

Functional Range Modifications:

As is showed previously in Table 39 all components within the product family are identified with Functional Range condition due to the existing geometrical scalability. Tables 40 to 42 summarise the geometrical modifications proposed for Palm, Gauntlet, Finger Pins, Wrist Pins and Wrist Rings. In the case of gauntlet (Tables 40 and 41), it is possible to generate two or more modularisation alternatives. Therefore, it is necessary to implement a decision-making process based on engineering parameters.

Table 40. Gauntlet Modification Alternative1 -Adjustable Gauntlet (Adjustment)

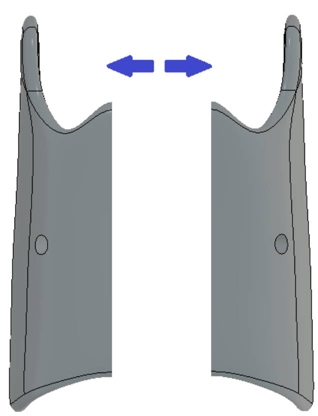
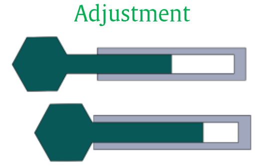
Adjustable Gauntlet	Implemented MAP
	Adjustment 
	Sustainability Benefits: a unique gauntlet can be used as a common component within the four PV required
Description: An adjustable gauntlet is designed to be adaptable through using elastic bands. Lateral holes for connectors do not require modification.	

Table 41. Gauntlet Modification Alternative 2 – Stacking Gauntlet

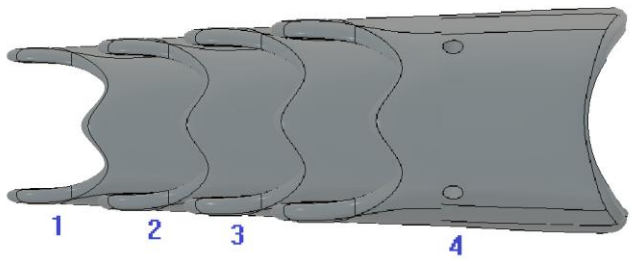
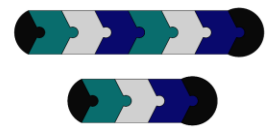
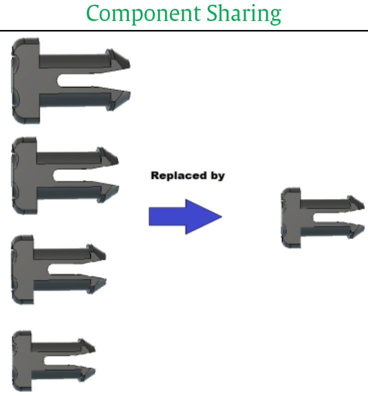
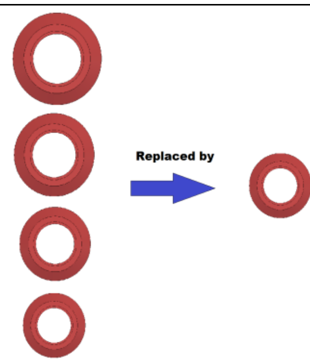
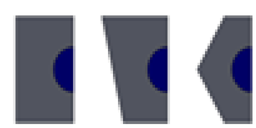
<table>
<tr><th>Stacking Gauntlet</th><th>Implemented MAP</th></tr>
<tr><td rowspan="2">
</td><td>Stacking
</td></tr>
<tr><td>Sustainability Benefits: a portion of the gauntlet can be shared and reused between two sizes, increasing the reusable mass within the product family.</td></tr>
<tr><td colspan="2">Description: To employ gauntlet stacking sections to generate gauntlet components for each PV. According to the figure, for instance, the sections 1 and 2 can provide the gauntlet for PV_1 and PV_5 (100%) and sections 2 and 3 can provide the gauntlet for PV_2 and PV_6 (110%). Additional joints are required between the gauntlet sections to entail the assembly and disassembly of stacking sections.</td></tr>
</table>

Table 42. Finger Pin, Wrist Pin and Wrist Ring Modification – Component Sharing

<table>
<tr><th>Finger Pin & Wrist Pin
Component Sharing</th><th>Wrist Ring
Component Sharing</th><th>Implemented MAP</th></tr>
<tr><td rowspan="2">
</td><td rowspan="2">
</td><td>Component Sharing
</td></tr>
<tr><td>Sustainability Benefits: The variety of finger pins, wrist pins and wrist rings is reduced from four to one. The use of a unique size entails the reuse of pins and rings within the PV.</td></tr>
<tr><td colspan="3">Description: Finger pin, wrist pin and wrist ring are designed to satisfy all the PV through a unique component. All holes within the components (palm, fingers and gauntlet) are designed with a unique diameter for all PV.</td></tr>
</table>

5.3.2.3 Hierarchy of OAP Alternatives

Once, the modularisation alternatives are generated, it is necessary to select the best alternative between the components with different modularisation options. In this case, the gauntlet can be modularised in two ways: using adjustment modularisation and using stacking. The hierarchy of such alternatives is developed through a technical trade-off between two main parameters: a) the overall Pugh Complexity Index-*P*, and b) the Overall assembly/disassembly complexity index – C_{TM}. Table 43 shows the values for *P* and C_{TM} and the decision parameter $\sqrt{P * C_{TM}}$ for each alternative. In conclusion, an adequate alternative is an Adjustable Gauntlet, which offers a decision parameter10% lower compared to the Stacking Gauntlet. It is important to clarify that the parameter $\sqrt{P * C_{TM}}$ measures the complexity involved in the selection of each alternative within the product family. However, the hierarchy can be developed through multi-criteria selection methods as well. Annex VI includes the detailed calculation for parameters mentioned in this design task.

Table 43. Technical comparison between modularisation alternatives for gauntlet

Alternatives	**Components**	**Overall Pugh Complexity Index (CI)**	**Overall Assembly-Disassembly Complexity Index (C_{TM})**	$\sqrt{CI * C_{TM}}$
Alternative 1: OAP Prosthetic hand with adjustable gauntlet	Modular Palm (x1) Adjustable Gauntlet (2 pieces) Fingers (x4) Thumb (x1) Thumb Adapter (x1) Finger Pins (x5) Wrist Pins (x2) Wrist Rings (x2)	16.01	232	60.9
Alternative 2: OAP Prosthetic hand with stacking gauntlet	Modular Palm (x1) Stackable Gauntlet (5 pieces) Fingers (x4) Thumb (x1) Thumb Adapter (x1) Finger Pins (x5) Wrist Pins (x2) Wrist Rings (x2)	18.7	244	67.5

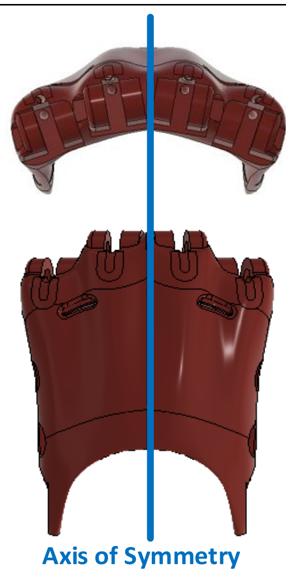
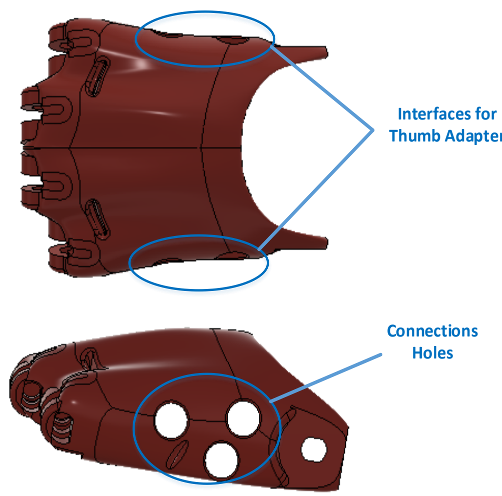
5.3.3 Basic Design

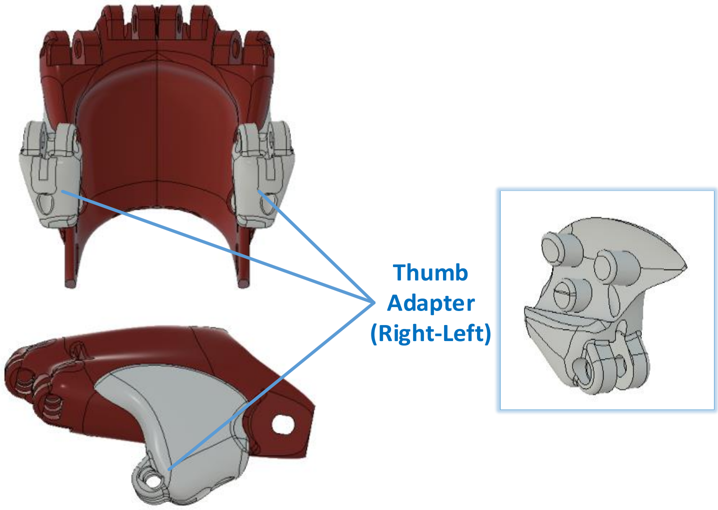
In this phase, all the modifications proposed in the previous stage of conceptual design are completed using the CAD software Autodesk Fusion 360®. Palm, gauntlet, pins, and rings are modified according to the conceptual modularisation proposed. The material selection is also included in this phase as a main contribution of the proposed method.

5.3.3.1 Arrangement of components and robust design

Tables 44 to 47 sum up the geometrical modifications for the prosthetic hand components.

Table 44. Basic Design - Palm with modular thumb

Palm - Thumb Modularization (Final Geometry)	
	
Adapter for thumb (Right and Left)	

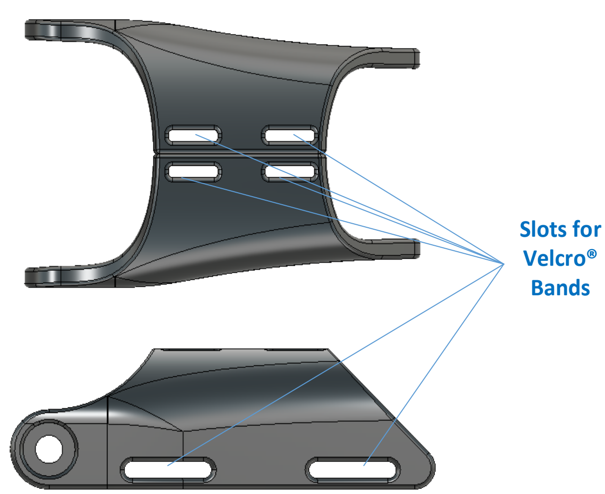


Description: The thumb modularisation was achieved through the following modifications:

a) To create a complete symmetric palm
b) To design an interface to assemble an adapter for thumb connection
c) To design an adapter which must provide an assembly interface between thumb and palm

Table 45.Basic Design - Adjustable Gauntlet

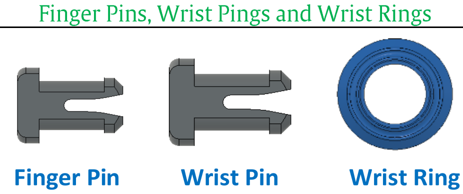
Adjustable Gauntlet



Description: The gauntlet was divided symmetrically into two equal sections. Slots were added to provide connection between sections through elastic bands.
The user is available to dismantle the gauntlet or change the elastic band length it is required to achieve higher comfort.

Table 46. Basic Design - Component Sharing for Pins and Rings

Finger Pins, Wrist Pings and Wrist Rings



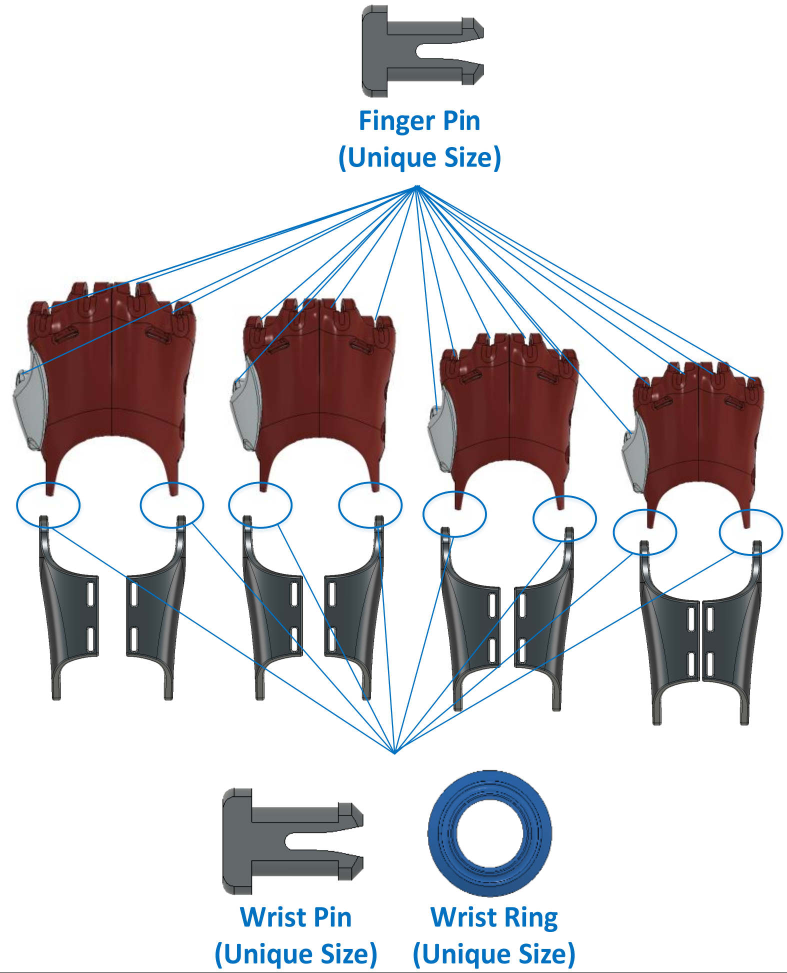
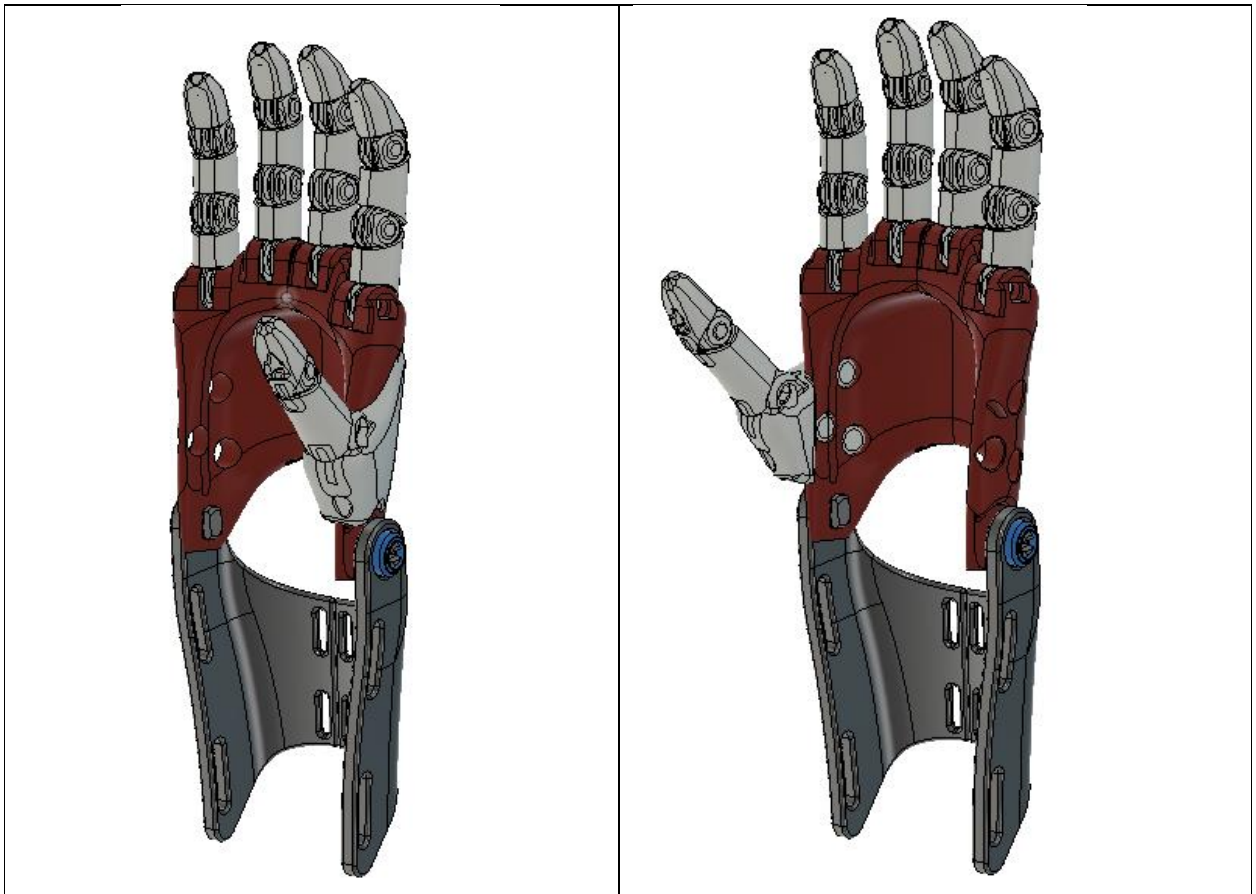
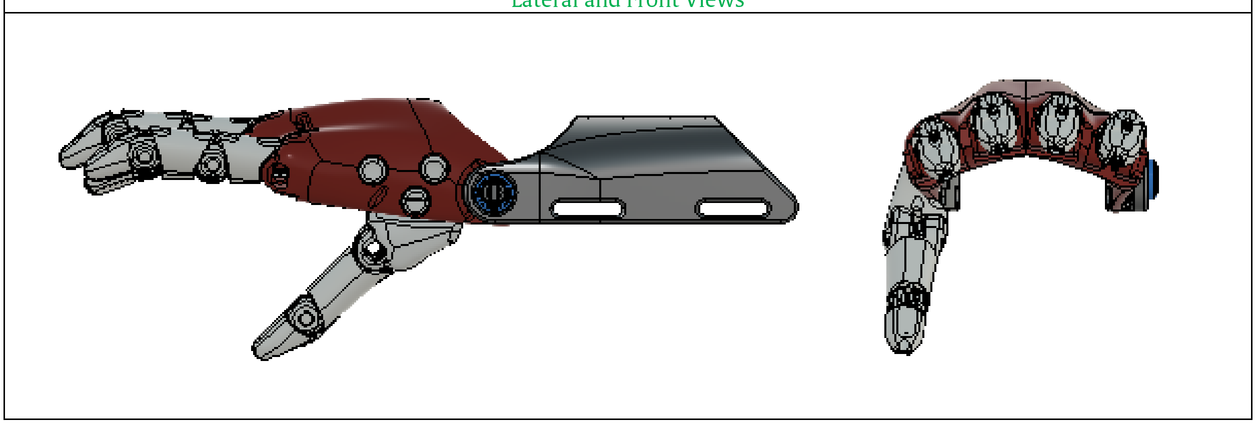

Description: All connectors (Pins and rings) were replaced by a single size. In addition, connection holes were adjusted to the unique size of pins.

Table 47.Overall view of the OAP Prosthetic Hand (Single Product – one size)

Right Hand	Left Hand



Lateral and Front Views



5.3.3.2 Materials Selection

The selection of manufacturing materials is obtained from the analysis of durability of each component in the product family. According to Table 48, the components with higher durability requirements are the Gauntlet, Finger Pins, Wrist Pins and Wrist Rings.

Table 48. Intensity of use of prosthetic hand components

Component	Intensity of Use	*Durability Requirement*
Palm	1 Product Variant	*Low*
Gauntlet	4 Product Variant	*High*
Thumb Adapter	1 Product Variant	*Low*
Thumb	1 Product Variant	*Medium*
Finger	1Product Variant	*Medium*
Finger Pin	4 Product Variant	*High*
Wrist Pin	4 Product Variant	*High*
Wrist Ring	4 Product Variant	*High*

Possible manufacturing materials for the prosthetic hand family are graphically compared in Figure 19. According to such comparison, the most suitable materials for the manufacturing of the prosthetic hand are PA11, PA12 and PLA. It is important to take into account that the original prosthetic hand is manufactured in PLA. Annex VII shows the values for environmental and mechanical durability.

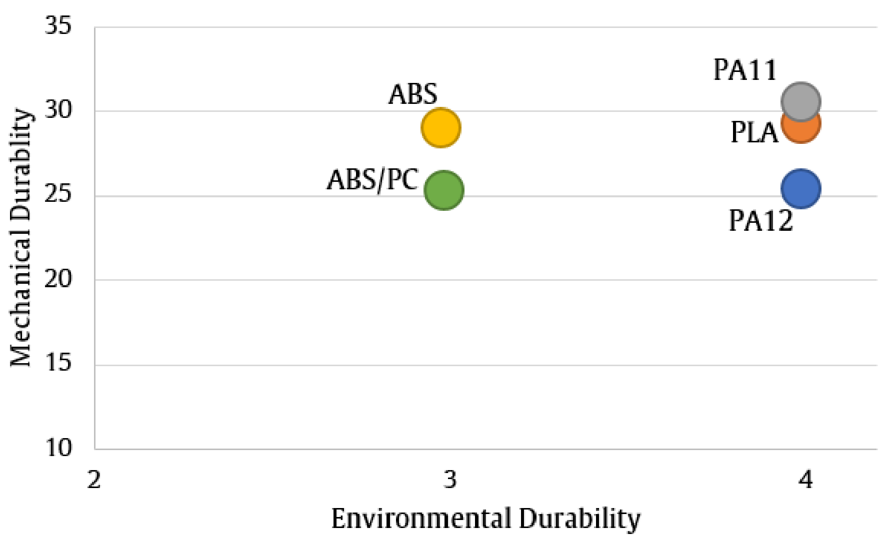


Figure 19. Environmental Durability Analysis for Manufacturing Materials

A graphical comparison of conventional sustainability indicators is developed to contrast the different alternatives of manufacturing materials for the prosthetic hand. Two radial charts are developed to contrast the manufacturing materials sustainability. Table 29 shows the scenarios in which each material is employed in the manufacture of all components (assuming an equal durability requirement). Besides, two mixed manufacturing scenarios were considered using PLA+PA11 and

PA12+PLA according to the durability requirement. Table 49 summarises the values for the mixed manufacturing scenarios. Figure 21 shows the radial chart comparison between the original design, PLA and mixed manufacturing scenarios. For the case of mixed manufacturing scenarios, the material with less durability is selected for palms, fingers, thumbs and thumb connectors and the material with more durability is selected for finger pins, wrist pins, wrist rings and gauntlets. All calculation results are summarised in detail in Annex VIII.

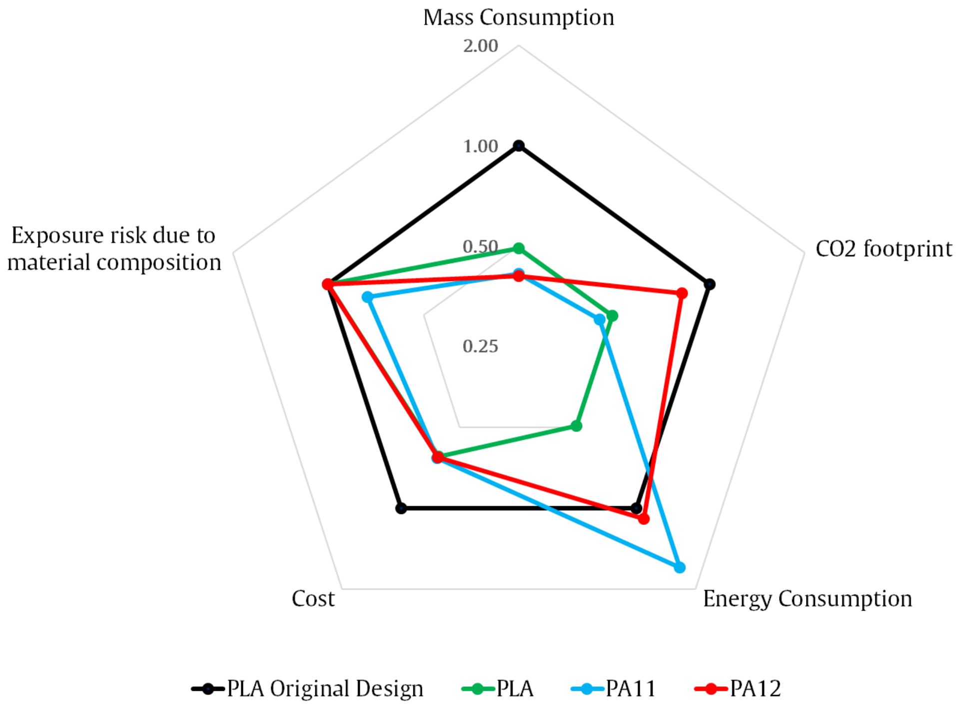


Figure 20. Radial Chart for comparison of manufacturing materials

Table 49. Mixed Scenarios for Manufacturing materials

Manuf. Scenario	1st material	Mass (kg)	2nd material	Mass (kg)
PLA	PLA All components	0.92	-	0
PLA+PA11	PLA Palm, Fingers, Thumb and Thumb connector	0.86	PA11 Finger Pins, Wrist Pins, Wrist Rings and Gauntlet	0.05
PA12+PLA	PA12 Palm, Fingers, Thumb and Thumb connector	0.71	PLA Finger Pins, Wrist Pins, Wrist Rings and Gauntlet	0.06

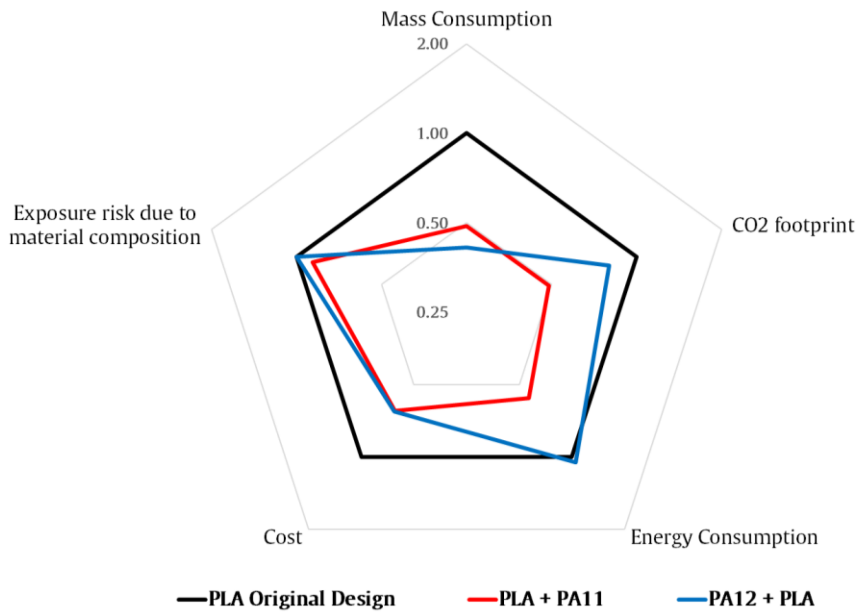


Figure 21. Radial Chart for Manufacturing Materials - Mixed Scenario

According to Figures 20 and 21, the most sustainable manufacturing scenarios are achieved when PLA and PLA+PA11 are employed as manufacturing material for all components. Figure 21 shows that PLA offers reductions in all conventional sustainability indicators, except for the exposure risk due to the material composition, which remains unchanged. Additionally, PLA+PA11 offers a reduction in all conventional sustainability indicators with slightly variations respect the PLA scenario. Figure 22 shows a comparison of both alternatives respect to the original design.

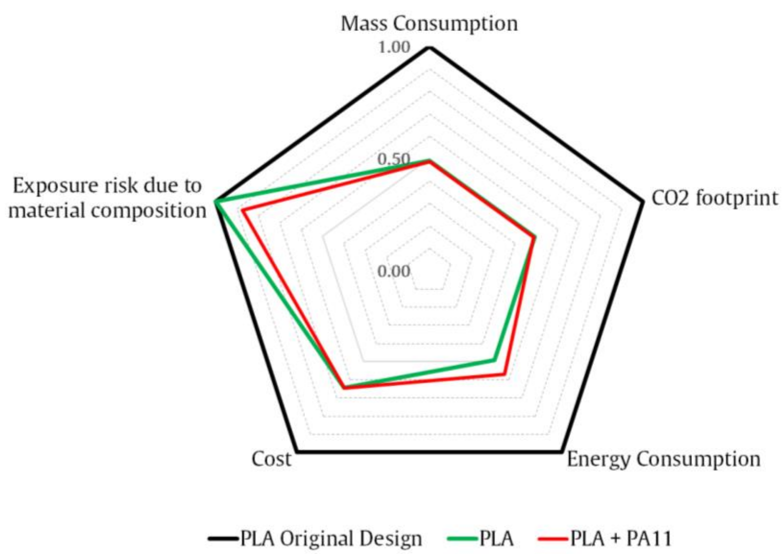


Figure 22. Comparison of best manufacturing alternatives respect to the original design

According to Figure 22, PLA and PLA+PA11 are suitable alternatives. However, the overall performance is very similar. Therefore, it is necessary to develop an additional step to select the best alternative according to the relative importance settled by the design team or designer. For this case study, the PLA alternative is selected to demonstrate the implementation of the remaining design tasks.

5.3.3.3 Performance Assessment and Comparison of Indicators

Table 50 summarises the calculation parameters and values for circularity and functional indicators. The circularity of the product family was improved regarding the reusability of components, from the functionality perspective; the new product family entails the reconfiguration within the PV due to the sharing of connectors (finger pin, wrist pin and wrist ring) and gauntlet. It is important to clarify that some indicators does not present initial values, in this case the data is remarked as Emerging Value (EV). Annex IX summarises the calculation of values listed in Table 50 for the open architecture design.

Circularity and functional indicators are measured according to the calculation parameters identified for both, the original design and the open architecture design (using PLA). The results are summarized in

Table *51*.

Table 50. Comparison of Circularity and Functional Indicators

Calculation Parameters	Units	Original Design-PLA	Open Architecture Design-PLA	Percentage Change
Total mass of the product family - Mt	kg	1.87	0.92	-40%
Total mass of reusable components - Mr	kg	0	0.062	EV
Recycling Efficiency - Ei	kg	0.9	0.9	-
Fraction of recyclable mass for component i - Fi	-	1	1	-
Mass of virgin feedstock in the PF - V	kg	0.187	0.092	-40%
Mass of unrecoverable waste in PF manuf. – Wu	kg	0	0	-
Mass of unrecoverable waste generated to produce recycled feedstock - Wf	kg	0.187	0.092	-40%
Mass of unrecoverable waste generated during recycling - Wr	kg	0.187	0.092	-40%
Number of product variants - P	-	8	8	-
Number of reconfigurations in the product family -R	-	0	6	
Number of components in the PF – n	-	128	78	-39%
Component Variety within the product Family C_V	-	28	25	-18%
Number of component variety capable of working in an operational range C_1	-	0	5	-
Number of component variety with more than one functionality C_2	-	0	4	-

Conventions: Desirable value, EV: Emerging Value

Table 51. Circularity and Functional Performance Indicators

Calculated Indicators	Original Design-PLA	Open Architecture Design-PLA	Percentual Change
Circularity Indicators			
Potential Reuse Index - RuI	0	0.06	EV
Potential Recycle Index - ReI	0.9	0.9	-
Linear Flow Index for Product Families - LFI	0.048	0.048	-
Functional Indicators			
Reconfiguration Index - RI	0	0.62	EV
Functional Range Index - FL	0	0.2	EV
Functional Variety Index - FV	0	0.16	EV

Conventions: Desirable value, EV: Emerging Value

A detailed analysis of results and discussion is developed in Chapter 6.

References

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Zuniga JM, Peck JL, Srivastava R, et al. Functional changes through the usage of 3D-printed transitional prostheses in children. Disability and rehabilitation. Assistive technology. Nov 8 2017:1-7

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Chapter 6

Results and Discussion

Highlights

- A comprehensive comparison of indicators is performed in terms of conventional sustainaiblity, circularity and funcitonal performance.
- A dicussion about the existing changes is presented regarding the improvements obtained from the values of indicators.
- The improvement of the design regarding overall complexity and number of components for the case study is also showed and discussed.

Contents

6.1 Introduction

This chapter includes analysis of results and discussion of data obtained in Chapter 5. Graphical comparisons are developed to contrast the performances comprehensively. The versions of prosthetic hand devices are compared (Original Design Vs Open Architecture Design) taking into account each indicator and the influence due to the modifications developed in Chapter 5. Results and discussion are divided according to the three main set of indicators proposed: Conventional Indicators, Circularity and Functional performance.

6.2 Analysis of Results

Once the implementation of the proposed method is completed, it is possible to summarise all results associated with conventional indicators, circularity and functional performance of the product family. The showed results of indicators are obtained from evaluating the manufacturing and end of life stages according to the case study nature. The sustainability impacts regarding the use stage are minimum for the case study, hence it is not considered in the developed analysis. The comparative results are shown graphically for the three performance metrics aforementioned.

6.2.1 Conventional Indicators

Five conventional sustainability indicators were employed to measure and compare the performance of the original product family vs the OAP product family of prosthetic devices. Summarises the five conventional sustainability indicators in a radial chart comparing three alternatives of manufacturing materials respect to the original design in a relative scale, which employs 1.0 as the reference value for the original product in all axis on the chart. It is important to clarify that the relative comparison proposed considers all indicators as a negative impact. Therefore, it is desirable to reduce the values in all axis of the chart. Thus values higher than 1.0 are not desirable. Meanwhile, values lower than 1.0 is desirable.

The results for each indicator are described in detail below:

Mass Consumption: in general, all alternatives provide an important reduction of mass consumption Mass consumption is the most important indicator, since environmental and economic impacts such as CO2 footprint, Energy Consumption and Manufacturing Cost are dependent on the mass involved in the product family. The main reduction in this parameter is due to the reductions of mass entailed by the modularisation of gauntlet and finger pins, wrist pins and wrist rings. Mass consumption is directly related to the resources depletion and indirectly decreases transport costs, manufacturing time and handling comfort for users.

CO2 Footprint (all lifecycle): all alternatives offer a reduction in the CO_2 footprint associated with the lifecycle of the product family of prosthetic hands. However, the most important reduction respect the original design is achieved when PLA or PLA+PA11 are employed as manufacturing materials (50% reduction).

Energy Consumption: the use of PA12+PLA incurs a slight increase in the energy consumption (less than 10%). On the other hand, the use of PLA+PA11 (50% reduction) also provides an important reduction of energy consumption compared to the original design. Nevertheless, the best alternative respect this indicator the use of PLA as the unique manufacturing material.

Cost: regarding manufacturing cost all alternatives provide a reduction compared to the original design. All values obtained are very similar, this due to the considerations of the economic model which considers the write-off time concerning the equipment invest. Therefore, the values obtained for cost are highly influenced by that consideration. The best results are achieved by the PLA and PLA+PA11 alternatives (35% reduction).

Exposure risk due to material composition: the values obtained for this indicator are equal for all alternatives considered. This situation is due to the quantitative nature of the indicator. For this indicator, the exposure risk is considered solely in the manufacturing and recycling stages, where the material is transformed using heat and mechanical processes. During the use stage, risks for users is minimum due to the product is used externally as a prosthetic device.

OVERALL SUSTAINABILITY PERFORMANCE: according to the Figure 23, and comparing the graphical results obtained from the three manufacturing alternatives, the best scenarios are represented by PLA and PLA+PA11. In the case of PLA, the area obtained by the vertices is smaller than the black pentagon, which represents the original design, and it offers reductions in all conventional sustainability indicators, except for the Exposure Risk due to the material composition.

Concerning the PLA+PA11 scenario, the area obtained is very similar to the PLA, offering a slight reduction in the Exposure Risk due to material composition but with a marginally larger value in energy consumption.

To select the manufacturing scenario in case of a draw, it is required an additional decision-making process (AHP or weighted weights). In this work, such activity is not considered into the methodological contributions. Therefore, the PLA scenario is selected to continue with the analysis of results and discussion. Figure 24 shows the reductions obtained in conventional sustainability indicators for the case of using PLA as the manufacturing material.

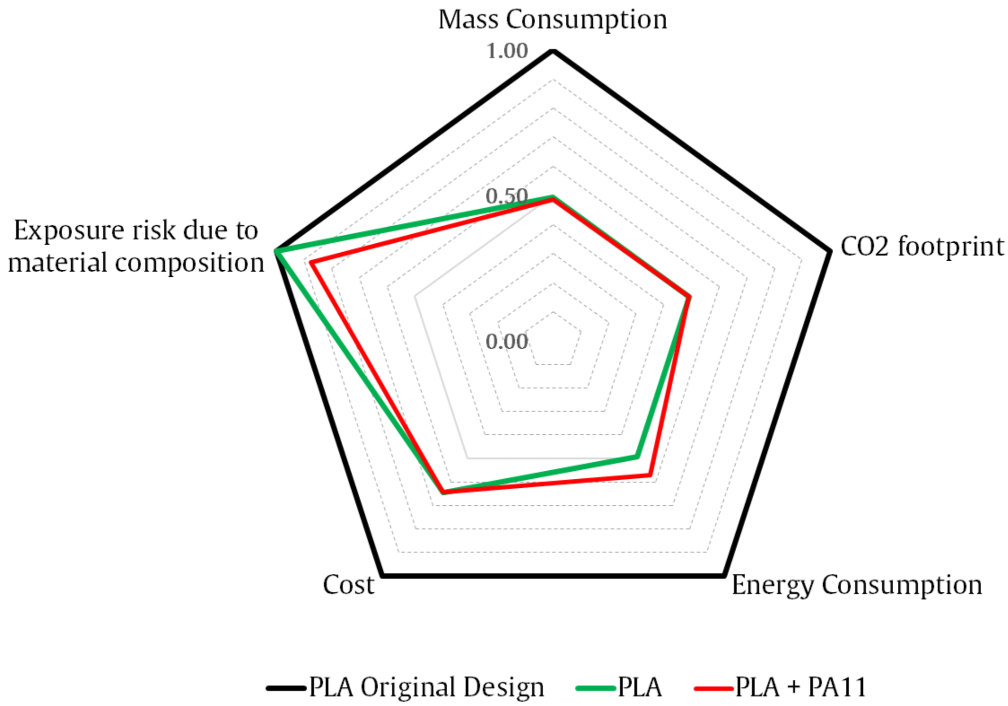


Figure 23. Radial chart for Conventional Sustainability Indicators

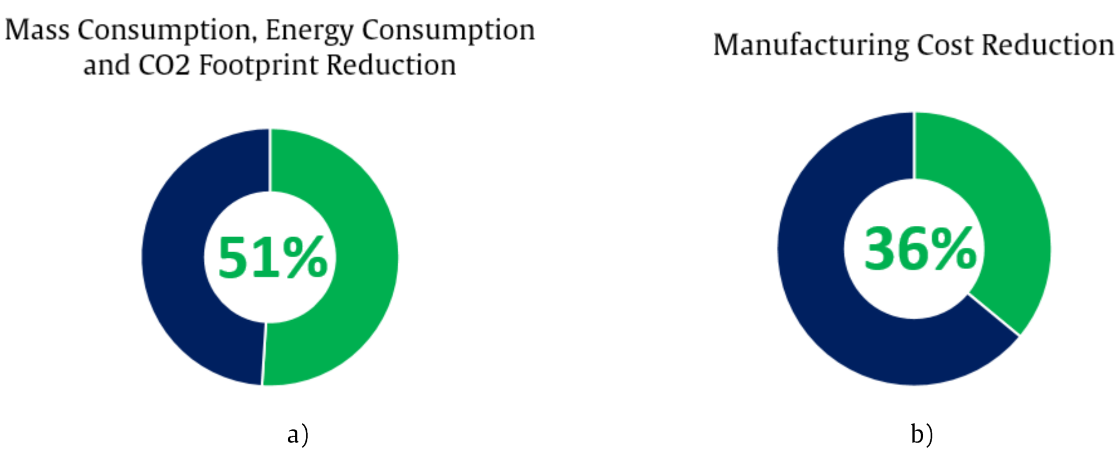


Figure 24. Percentual Reduction in Conventional Sustainability Indicators

It is important to clarify that reductions obtained in conventional indicators are only due to the mass reduction obtained in the new design. PLA is employed by both designs the original and the obtained through the proposed methodology. In the case of changing the manufacturing material, it is also convenient to use relative indicators respect to the mass of each product family.

6.2.2 Circularity Indicators

Figure 25 summarises the change of values in circularity indicators comparing the original design and the open architecture design (both using PLA as manufacturing material). In this case, the potential reuse emerges as a new value due to the reusable components within the product family. Potential Recycle Index and Linear Flow Index remain unchangeable due to the manufacturing material did not change respect the original design.

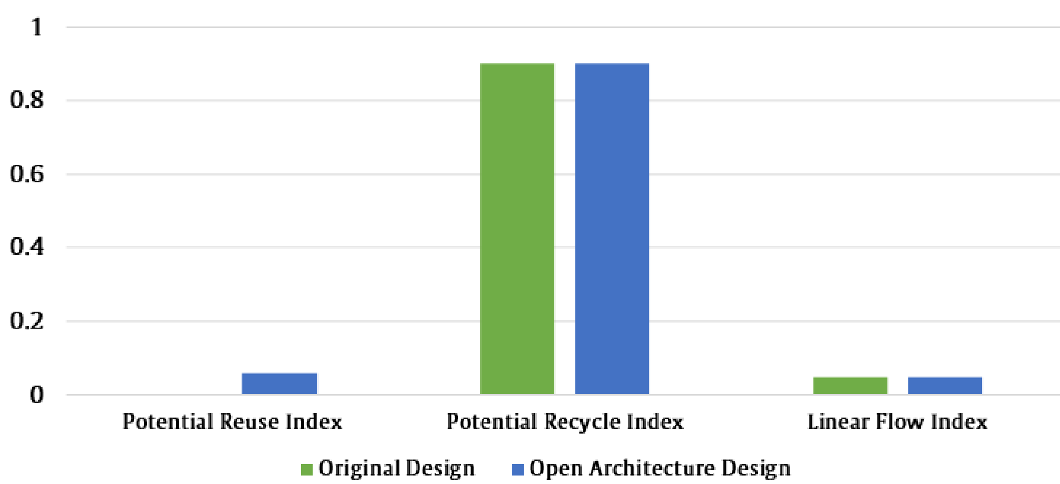


Figure 25. Comparison of Circularity Indicators

6.3 Discussion

Discussion of results is divided into three performance sections: a) Conventional Indicators, b) Circularity Indicators and c) Functional Indicators, according to the data obtained and information summarised in the previous chapter. Each section is described in detail below.

Sustainability Conventional Indicators

Regarding sustainable conventional indicators, the design modifications can change two main parameters: the geometry and the manufacturing material. In this case, the most sustainable alternative involves the use of the same material respect the original design (PLA). Therefore, the improvement in conventional Sustainability indicators is due solely to the geometrical changes, which represent an important reduction in the mass of the whole product family (51%). Such reduction is due to the reuse of components (finger pins, wrist pins, wrist rings and adjustable gauntlet) within the product family.

The saving of mass, therefore, improves the performance of all indicators, which are measured regarding mass. If the mass is reduced, the CO_2 footprint, the energy consumption, and manufacturing costs are reduced proportionally. In the particular case of manufacturing cost, the reduction of mass provided by the reuse of components diminishes the manufacturing time for a complete product family.

Circularity Performance

In the case of circularity indicators, the values remain unchangeable for Potential Recycle Index (ReI) and Linear Flow Index (LFI). This is due to the definitions of such indicators, which are conceived as a relative measurement regarding the masses within the product or product family. The material for both, the original design and the open architecture design is the same (PLA), and due to this, the recycling properties, recycle efficiency and waste generated was assumed equal for both indicators.

In the case of Potential Reuse Index (RuI), the reuse of components (finger pins, wrist pins, wrist rings and adjustable gauntlet) during the upgrading of products provide a value for the parameter Total Mass of Reusable Components – Mr, which represent a value for the RuI different from zero. This value is a positive result of the modularisation process. However, the reusable mass just represents 6% of the whole mass of the product family, whence this parameter is susceptible of improvement until reach a higher value.

Functional Performance

In this aspect, the improvement obtained is significant for all indicators. The functional indicators are based on the relationship benefit/resources, since the resources to achieve the functionalities are lower for the open architecture design, the expected values for the indicators are all different from zero, unlike the original design which has zero values for all these three indicators.

Reconfiguration Index (RI), Functional Range index (FV) and Functional Variety index (FV) appear as emergent values due to:

- Reconfigurations enabled by the adjustable gauntlet from PV_1 to PV_4 and PV_5 to PV_8 according to the growth of children. The original design offers a RI equal to zero, due to the absence of reconfigurable components.
- Four Components of the open architecture design can provide more than one functionality. The palm is a common component that entails the assembly of right or left handled products.

Original design does not provide any component to offer more than one overall functionality within the product family.

- Three components (finger pins, wrist pins and wrist rings) can work in all product variants along the growth of the product family. Such advantage generates values in the Functional Range Index different from zero. The original design does not consider any component to work in an operational range; all components are designed to work in a unique product variant.

6.4 Other considerations

Table 52 includes the comparison of the component-Product Variant Relationship. As result of the methodological contributions proposed, the number of component variety is lower, and several components are related to more than one Product Variant. In the case of Finger Pins, Wrist Pins and Wrist Rings, which are related to all existing product variants. The comparison showed in Table 52 provides an easy demonstration of the benefits obtained through the use of the proposed methodological contributions.

Table 52. Comparison of Component - Product Variant Relationship, Original Design Vs Open Architecture Design

Original Design

Component Variety	Product Variant							
	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8
Right Palm$_1$	1	-	-	-	-	-	-	-
Right Palm$_2$	-	1	-	-	-	-	-	-
Right Palm$_3$	-	-	1	-	-	-	-	-
Right Palm$_4$	-	-	-	1	-	-	-	-
Left Palm$_1$	-	-	-	-	1	-	-	-
Left Palm$_2$	-	-	-	-	-	1	-	-
Left Palm$_3$	-	-	-	-	-	-	1	-
Left Palm$_4$	-	-	-	-	-	-	-	1
Gauntlet$_1$	1	-	-	-	1	-	-	-
Gauntlet$_2$	-	1	-	-	-	1	-	-
Gauntlet$_3$	-	-	1	-	-	-	1	-
Gauntlet$_4$	-	-	-	1	-	-	-	1
Finger$_1$	1	-	-	-	1	-	-	-
Finger$_2$	-	1	-	-	-	1	-	-
Finger$_3$	-	-	1	-	-	-	1	-
Finger$_4$	-	-	-	1	-	-	-	1
Thumb$_1$	1	-	-	-	1	-	-	-
Thumb$_2$	-	1	-	-	-	1	-	-
Thumb$_3$	-	-	1	-	-	-	1	-
Thumb$_4$	-	-	-	1	-	-	-	1
Finger Pin$_1$	1	-	-	-	1	-	-	-
Finger Pin$_2$	-	1	-	-	-	1	-	-
Finger Pin$_3$	-	-	1	-	-	-	1	-
Finger Pin$_4$	-	-	-	1	-	-	-	1
Wrist Pin$_1$	1	-	-	-	1	-	-	-
Wrist Pin$_2$	-	1	-	-	-	1	-	-
Wrist Pin$_3$	-	-	1	-	-	-	1	-
Wrist Pin$_4$	-	-	-	1	-	-	-	1
Wrist Ring$_1$	1	-	-	-	1	-	-	-
Wrist Ring$_2$	-	1	-	-	-	1	-	-
Wrist Ring$_3$	-	-	1	-	-	-	1	-
Wrist Ring$_4$	-	-	-	1	-	-	-	1

Open Architecture Design

Component Variety	Product Variant							
	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8
Palm$_1$	1	-	-	-	1	-	-	-
Palm$_2$	-	1	-	-	-	1	-	-
Palm$_3$	-	-	1	-	-	-	1	-
Palm$_4$	-	-	-	1	-	-	-	1
Gauntlet$_1$	1	1	1	1	1	1	1	1
Finger$_1$	1	-	-	-	1	-	-	-
Finger$_2$	-	1	-	-	-	1	-	-
Finger$_3$	-	-	1	-	-	-	1	-
Finger$_4$	-	-	-	1	-	-	-	1
Thumb$_1$	1	-	-	-	1	-	-	-
Thumb$_2$	-	1	-	-	-	1	-	-
Thumb$_3$	-	-	1	-	-	-	1	-
Thumb$_4$	-	-	-	1	-	-	-	1
Right Thumb adaptor$_1$	1	-	-	-	-	-	-	-
Right Thumb adaptor$_2$	-	1	-	-	-	-	-	-
Right Thumb adaptor$_3$	-	-	1	-	-	-	-	-
Right Thumb adaptor$_4$	-	-	-	1	-	-	-	-
Left Thumb adaptor$_1$	-	-	-	-	1	-	-	-
Left Thumb adaptor$_2$	-	-	-	-	-	1	-	-
Left Thumb adaptor$_3$	-	-	-	-	-	-	1	-
Left Thumb adaptor$_4$	-	-	-	-	-	-	-	1
Finger Pin$_1$	1	1	1	1	1	1	1	1
Wrist Pin$_1$	1	1	1	1	1	1	1	1
Wrist Ring$_1$	1	1	1	1	1	1	1	1

Chapter 7

Conclusions and Future Works

7.1 Conclusions

Sustainability requirements and the mass individualisation trends from the market are not compatible issues. Therefore, the product design process must be addressed to increase circular economy and sustainability strategies to face that problem.

To face this challenge, this thesis aimed to propose methodological contributions focused on the use of modular architecture principles to convert conventional product families into OAP families, capable of reuse components and interact more efficiently among all its constructive components. Modularization algorithms, analysis of product family complexity, sustainability indicators, and conventional design methods were combined to propose a robust method to increase the overall performance of product families regarding material and energy consumption, CO_2 footprint, cost among others.

Based on the results obtained from this thesis, the following issues were verified:

- The use of Modular Architecture Principles – MAPs is advantageous from the sustainability perspective, due to the ability to reuse more components in different product variants and configurations. Such reuse involves considerable benefits in sustainability, circularity and functional indicators.

- The use of product families facilitates entails the design of products with diverse functionalities and operational ranges. The modularity is a key strategy to develop robust product families using less resources compared to conventional product families. In this thesis, the product family obtained is denominated open architecture product family, which means the ability of exchange and remove components not only in the manufacturing stage but also in the use and final disposal phases.
- The sustainability improvements in any existing design are achieved through two main modifications: geometry and manufacturing materials. Hence, the sustainability

enhancements should be oriented to optimise the geometrical shapes of products (related to assembly, disassembly and fits) and the materials selection, which is associated with particular sustainability properties such as CO_2 footprint, energy consumption among others. Nevertheless, the primary objective is to reduce the number and mass of components and the use of a highly sustainable material (recyclable, reusable, biodegradable among others).

- The design contributions proposed in this thesis require an additional attribute: the consumer/user consciousness about sustainability and the need for implementing circular economy strategies. Without that consciousness, the design does not provide any useful benefit to the society.

- To successfully implement strategies for sustainable product design is necessary to consider the entire product families attributes, the functional parameters suitable for modularization and the behavioural consciousness of the customer about the circular economy benefits. This thesis is focused on the management of the useful information flow to identify suitable parameters of variation and the contemplation of modular architecture principles for each components into the product family. The contributions for each stage are listed below:

    - **Needs Clarification stage:** the establishment of variation parameters and attributes, identification and analysis of the product variants.
    - **Conceptual Design**: the generation and comparison of modularized alternatives for each constructive component in the product family.
    - **Basic Design**: the selection of materials based on durability measurements, the technical comparison of sustainability indicators regarding the different alternatives for manufacturing materials.

- The implicit social benefit through of methodology is always positive by the following reasons: 1) greater accessibility of society to enjoy the benefits of the product, due to its low cost. And 2) the product family architecture obtained with this methodology to require less raw material, less material quantity processed, less material quantity to recycle, therefore less energy required, contributing to the planet sustainability for the next generations.

7.2 Future Works

The proposed methodological contributions described in this thesis are subjected to different limitations and assumptions. Future works should be oriented to cover such constraints accurately. Main future works are summarised in the list below.

- To modify or verify the proposed methodological contributions to consider product families without progressive size growth (in series). The method is focused on increasing the reusability and share of components among different product variants, which are progressive,replaced due to customer requirements. However, product families are not only designed to cover that scenario. Parallel product variants should also be considered, manufacturing common modules according to similar use scenarios and special modules for very particular use scenarios (additional personalization).

- The proposed method does not consider the reparability of components. It is only focused on simple components (Each component is comprised of one unique element). For more complex products, the modularisation algorithms and analysis can be more time consuming and tedious. Therefore, several modifications are required to cover more complex components, products and product families.

- The proposed sustainability indicators are designed to cover the conventional sustainability topics, the circularity of products and the functional performance regarding a functional variety and operational range. However, such indicators need to be assessed using more robust sets of metrics to guarantee a holistic sustainability measurement. The design or use of more indicators depends on the nature of the case and the designer's criteria.

- To follow further research efforts it is highly recommendable to employ case studies to compare and analyse real impacts from the modifications performed in early design phases. Massive manufacturing products can be suitable for further analysis taking into account the long term impact during all lifecycle stages. It is necessary to contemplate the manufacturing of product prototypes and compare results using real and experimental information, especially concerning conventional sustainability impacts and durability of components.

Annexes

Contents

ANNEX I: Measurement Scale for Health Risk

Annex Table 1. Health Risk measurement scale (Material)

		REACH valuation				
		0 – 0.2	0.21-0.4	0.41-0.6	0.61-0.8	0.81-1.0
Flammability	Non-Flammable					
	Self-Extinguishing					
	Slow-Burning					
	Highly Flammable					
Conventions: Very Low Low Medium High Very High						

Annex Table 2. Qualitative Overall Level

Level	Qualitative Level
Very Low	1
Low	2
Medium	3
High	4
Very High	5

REACH Valuation: Registration, Evaluation, Authorization and Restriction of Chemicals. This standard aims to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances.

Flammability: defined as the condition in which high temperature or flame in the presence of oxygen creates the risk of burning. Many materials are flammable: exposed to a flame they combust, though some will self-extinguish when the flame is removed.

ANNEX II: Pugh Complexity Index & Assembly/Disassembly Complexity Index

Pugh Complexity Index (Pugh, 1996)

$$CI = \sqrt[3]{N_c N_p N_i}$$

Where:

$N_c: Number\ of\ components\ or\ parts\ within\ the\ product\ family$

$N_c: Number\ of\ pieces\ within\ the\ product\ family$

$N_c: Number\ of\ contacting\ interfaces\ within\ the\ product\ family$

Assembly Disassembly Complexity Index (Mesa et al., 2017)[4]

Annex Table 3. Assembly/Disassembly Measurement

Product variant reconfiguration	Module relationship	Brief description	Number of operations T	Complexity of task C_t	Overall complexity $O_c = T * C_t$
PV_0–PV_1	adM_{11}	Description of the operation	Number of operations to assembly and disassembly M_{11}	Numeric valuation (1–5)	Result of the multiplication $T * C_t$
	…	…	…	…	…
	adM_{21}				
	adM_{mk}	…	Number of operations to assembly and disassembly M_{mk}	Numeric valuation (1–5)	…
…	…	…	…	…	…
PV_n–PV_1	…	…	…	…	…
PV_n–PV_{n-1}	…	…	…	…	…
	Total overall complexity in whole product configurations C_{TM}				Sum of values

Note: *a*Mx: Assembly of module x; *d*Mx: Disassembly of module x; *ad*Mx: Assembly and Disassembly of module x.

Annex Table 4. Complexity of Task measurement

Factor	Level	Description	Score
F1: Handling	One hand	The task can be performed with one hand	0.25
	Two hands	The task requires both hands	0.5
	More than two hands	The task requires more than one person	1.0
F2: Insertion alignment of joint elements	Very low	No alignment required	0
	Low	½ rotation required 180°	0.25
	Medium	¾ rotation required 270°	0.5
	High	One rotation required 360°	0.75
	Very high	Two rotation required 720°	1.0
F3: Type of tool	No tool requirement	The task does not require a tool. Manual assembly	0.25
	Conventional tool	The task requires a screwdriver, wrench or similar	0.5
	Specialised tool	The task requires power assisted or specialised tools	1.0
F4: Type of interface	Easy	Interface with intuitive adjustment	0.25
	Normal	Interface with specific alignment	0.5
	Difficult	Interface requires fasteners	1.0
F5: Fixing fevices	Not required	Fixing devices not required	0.0
	Conventional	Requires the use of vises or bench vises	0.5
	Specialised	Requires the use of specialised fixing devices	1.0

[4] Mesa, J. A., Esparragoza, I. & Maury, H., 2017. Development of a metric to assess the complexity of assembly/disassembly tasks in open architecture products. *International Journal of Production Research*, Issue First Online.

ANNEX III: Scale to Measure Environmental Durability

Table 53. Environmental Durability Measurement

Sub-criteria	Valuation Levels for all sub-criteria	Environmental Durability (D_{env})	Durability Levels
Water Resistance (R_w)	Excellent-4, Acceptable-3, Limited-2, Unacceptable-1	14-16	5-Very High
Acids Resistance (R_a)		11-13	4-High
Organic Solvents (R_o)		9-10	3-Medium
Chemical Resistance (R_c)		7-8	2-Low
UV Radiation Resistance (R_{UV})		4-6	1-Very Low

ANNEX IV: Diagnostic values for Case Study

Masses of the Prosthetic Hand family

Annex Table 5. Detailed Mass Calculation for Prosthetic Hand Family (Case Study)

	Part	Mass	Qty	Total	Total Product (g)
100%	Palm	82.88	1	82.88	158.99
	Gauntlet	44.38	1	44.38	
	Finger	5.87	4	23.48	
	Thumb	4.67	1	4.67	
	Finger Pin	0.36	5	1.8	
	Wrist Pin	0.41	2	0.82	
	Wrist Ring	0.48	2	0.96	
	Part	Mass	Qty		
110%	Palm	106.49	1	106.49	204.04
	Gauntlet	56.55	1	56.55	
	Finger	7.65	4	30.6	
	Thumb	6.07	1	6.07	
	Finger Pin	0.43	5	2.15	
	Wrist Pin	0.5	2	1	
	Wrist Ring	0.59	2	1.18	
	Part	Mass	Qty		
120%	Palm	133.85	1	133.85	256.01
	Gauntlet	70.62	1	70.62	
	Finger	9.67	4	38.68	
	Thumb	7.66	1	7.66	
	Finger Pin	0.52	5	2.6	
	Wrist Pin	0.6	2	1.2	
	Wrist Ring	0.7	2	1.4	
	Part	Mass	Qty		
130%	Palm	165.75	1	165.75	316.23
	Gauntlet	86.9	1	86.9	
	Finger	12.01	4	48.04	
	Thumb	9.44	1	9.44	
	Finger Pin	0.6	5	3	
	Wrist Pin	0.71	2	1.42	
	Wrist Ring	0.84	2	1.68	
TOTAL PRODUCT FAMILY (Left and Right hand) x2 (g)					1870.54

Manufacturing Time

Annex Table 6. Detailed Manufacturing Time Calculation for Prosthetic Hand Family (Case Study)

Manufacturing Cluster (Additive FDM)	Manufacturing time (h)	Total Manufacturing time (h) Variants PV_1-PV_4
Palms	41.6	92.96 (185.9 for the whole product family)
Gauntlets	29.81	
Fingers + Thumbs	17.8	
Finger Pin, Wrist Pins and Wrist Rings	3.75	

Calculation of Energy Consumption[5]

The value employed to calculate the Energy Consumption (lifecycle) for the case study (using PLA as manufacturing material) is **75.1 MJ/kg**. The Energy Consumption is obtained from the multiplication of this value and the mass consumption.

CO_2 Footprint[3]

The value employed to calculate the CO_2 footprint (lifecycle) for the case study (original design) is **5.3 kg CO_2/kg**. CO_2 footprint is obtained from the multiplication of this value and the mass consumption.

Manufacturing Cost

Manufacturing Cost is calculated using the cost model showed in chapter 4.

$$Manufacturing\ Cost = m * C_m + T\left(\frac{C_c}{t_{wo}} + C_{oh}\right)$$

Calculation parameters are listed below[3]:

m: 1.87 kg

C_m: 2.4 USD/kg

T: 185.9 hours (eight product variants – all product family)

C_c: 20000 USD

t_{wo}: 17520 hours

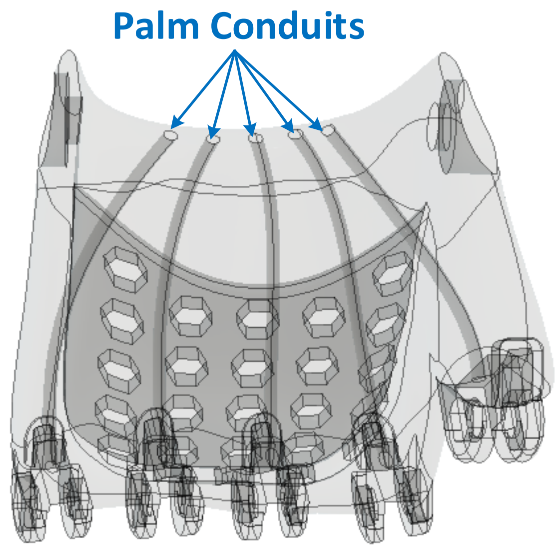
C_{oh}: 5 USD per hour

Health Risk Exposition

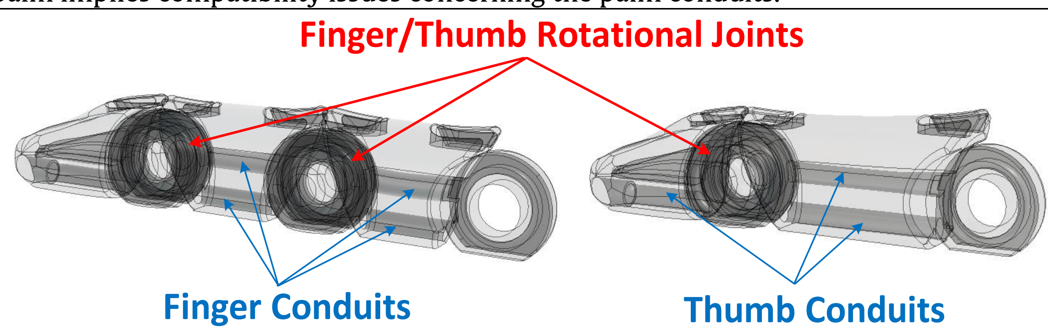
This sustainability indicator is calculated according to the scale proposed in Annex II.

[5] Values obtained from CES Selector Software 2016. Granta Design

ANNEX V: Detailed Internal Structure of Palm and Fingers



Palm conduits provide channels for cords from fingers to the gauntlet. Separation or discretization of the palm implies compatibility issues concerning the palm conduits.



Finger conduits and rotational joints are connected in the current finger design. Separation of finger sections involves the need of new connectors and increase of complexity for assembly and disassembly.

ANNEX VI: Calculation of decision parameters for hierarchy of alternatives

Calculation of Assembly Disassembly Complexity Index

Annex Table 7. Summary of components per Alternative

Component		Variant	Convention		Component	Variant	Convention		Component	Variant	Convention
Palm		Right Palm 100%	M_{11}		Palm	Right Palm 100%	A_{11}		Palm	Right Palm 100%	A_{11}
		Right Palm 110%	M_{12}			Right Palm 110%	A_{12}			Right Palm 110%	A_{12}
		Right Palm 120%	M_{13}			Right Palm 120%	A_{13}			Right Palm 120%	A_{13}
		Right Palm 130%	M_{14}			Right Palm 130%	A_{14}			Right Palm 130%	A_{14}
Gauntlet		Gauntlet 100%	M_{21}		Gauntlet	Adjustable Gauntlet P_1	A_{21}		Gauntlet	Stacking Gauntlet P_1	A_{21}
		Gauntlet 110%	M_{22}			Adjustable Gauntlet P_2	A_{22}			Stacking Gauntlet P_2	A_{22}
		Gauntlet 120%	M_{23}		Finger	Finger 100%	A_{31}			Stacking Gauntlet P_3	A_{23}
		Gauntlet 130%	M_{24}			Finger 110%	A_{32}			Stacking Gauntlet P_4	A_{24}
Finger		Finger 100%	M_{31}			Finger 120%	A_{33}			Stacking Gauntlet P_5	A_{25}
		Finger 110%	M_{32}			Finger 130%	A_{34}		Finger	Finger 100%	A_{31}
		Finger 120%	M_{33}		Thumb	Thumb 100%	A_{41}			Finger 110%	A_{32}
		Finger 130%	M_{34}			Thumb 110%	A_{42}			Finger 120%	A_{33}
Thumb		Thumb 100%	M_{41}			Thumb 120%	A_{43}			Finger 130%	A_{34}
		Thumb 110%	M_{42}			Thumb 130%	A_{44}		Thumb	Thumb 100%	A_{41}
		Thumb 120%	M_{43}		Thumb Adapter	Thumb Adapter 100%	A_{51}			Thumb 110%	A_{42}
		Thumb 130%	M_{44}			Thumb Adapter 110%	A_{52}			Thumb 120%	A_{43}
Finger Pin		Finger 100%	M_{51}			Thumb Adapter 120%	A_{53}			Thumb 130%	A_{44}
		Finger 110%	M_{52}			Thumb Adapter 130%	A_{54}		Thumb Adap.	Thumb Adapter 100%	A_{51}
		Finger 120%	M_{53}		Finger Pin	Finger 100%	A_{61}			Thumb Adapter 110%	A_{52}
		Finger 130%	M_{54}		Wrist Pin	Wrist Pin 100%	A_{71}			Thumb Adapter 120%	A_{53}
Wrist Pin		Wrist Pin 100%	M_{61}		Wrist Ring	Wrist Ring 100%	A_{81}			Thumb Adapter 130%	A_{54}
		Wrist Pin 110%	M_{62}						Finger Pin	Finger 100%	A_{61}
		Wrist Pin 120%	M_{63}						Wrist Pin	Wrist Pin 100%	A_{71}
		Wrist Pin 130%	M_{64}						Wrist Ring	Wrist Ring 100%	A_{81}
Wrist Ring		Wrist Ring 100%	M_{71}								
		Wrist Ring 110%	M_{72}								
		Wrist Ring 120%	M_{73}								
		Wrist Ring 130%	M_{74}								

Annex Table 8. Assembly/Disassembly Complexity Index C_{TM} for Original Design

Product Variant Reconfiguration	Module relationship	Operation	Number of operations T	Complexity task level C_t	O_c
$PV_0 - PV_1$	aM_{11}	Manual Assembly	5	1.75	8.75
	aM_{21}	Manual Assembly	2	1.75	3.5
	aM_{31}	Manual Assembly	4	2	8
	aM_{41}	Manual Assembly	1	2	2
	aM_{51}	Manual Assembly	5	1.5	7.5
	aM_{61}	Manual Assembly	2	1.5	3.5
	aM_{71}	Manual Assembly	2	1.5	3
$PV_1 - PV_2$	aM_{11}	Manual Assembly	5	1.75	8.75
	aM_{21}	Manual Assembly	2	1.75	3.5
	aM_{31}	Manual Assembly	4	2	8
	aM_{41}	Manual Assembly	1	2	2
	aM_{51}	Manual Assembly	5	1.5	7.5
	aM_{61}	Manual Assembly	2	1.5	3.5
	aM_{71}	Manual Assembly	2	1.5	3
$PV_2 - PV_3$	aM_{11}	Manual Assembly	5	1.75	8.75
	aM_{21}	Manual Assembly	2	1.75	3.5
	aM_{31}	Manual Assembly	4	2	8
	aM_{41}	Manual Assembly	1	2	2
	aM_{51}	Manual Assembly	5	1.5	7.5
	aM_{61}	Manual Assembly	2	1.5	3.5
	aM_{71}	Manual Assembly	2	1.5	3
$PV_3 - PV_4$	aM_{11}	Manual Assembly	5	1.75	8.75
	aM_{21}	Manual Assembly	2	1.75	3.5
	aM_{31}	Manual Assembly	4	2	8
	aM_{41}	Manual Assembly	1	2	2
	aM_{51}	Manual Assembly	5	1.5	7.5
	aM_{61}	Manual Assembly	2	1.5	3.5
	aM_{71}	Manual Assembly	2	1.5	3
		Overall Assembly/Disassembly complexity Index C_{TM}			145

Annex Table 9. Assembly/Disassembly Complexity Index C_{TM} for Alternative 1

Product Variant Reconfiguration	Module relationship	Operation	Number of operations T	Complexity task level C_t	O_c
$PV_0 - PV_1$	aM_{11}	Manual Assembly	5	1.75	8.75
	aM_{21}	Manual Assembly	1	1.75	1.75
	aM_{22}	Manual Assembly	1	1.75	1.75
	aM_{31}	Manual Assembly	4	2	8
	aM_{41}	Manual Assembly	1	2	2
	aM_{51}	Manual Assembly	1	1.75	1.75
	aM_{61}	Manual Assembly	5	1.5	7.5
	aM_{71}	Manual Assembly	2	1.5	3
	aM_{81}	Manual Assembly	2	1.25	2.5
$PV_1 - PV_2$	dM_{11}	Manual Disassembly	5	1.75	8.75
	$*aM_{12}$	Manual Assembly	5	1.75	8.75
	adM_{21}	Manual Assembly/Disassembly	2	1.75	3.5
	adM_{22}	Manual Assembly/Disassembly	2	1.75	3.5
	dM_{31}	Manual Disassembly	4	1.75	7
	aM_{32}	Manual Assembly	4	2	8
	dM_{41}	Manual Disassembly	1	1.75	1.75
	aM_{42}	Manual Assembly	1	2	2
	aM_{52}	Manual Assembly	1	1.75	1.75
	$*adM_{61}$	Manual Assembly/Disassembly	8	1.5	12
	$*adM_{71}$	Manual Assembly/Disassembly	2	1.5	3
	daM_{81}	Manual Assembly/Disassembly	4	1.25	5
$PV_2 - PV_3$	dM_{12}	Manual Disassembly	5	1.75	8.75
	$*aM_{13}$	Manual Assembly	5	1.75	8.75
	adM_{21}	Manual Assembly/Disassembly	2	1.75	3.5
	adM_{22}	Manual Assembly/Disassembly	2	1.75	3.5
	dM_{32}	Manual Disassembly	4	1.75	7
	aM_{33}	Manual Assembly	4	2	8
	dM_{42}	Manual Disassembly	1	1.75	1.75
	aM_{43}	Manual Assembly	1	2	2
	aM_{53}	Manual Assembly	1	1.75	1.75

Product Variant Reconfiguration	Module relationship	Operation	Number of operations T	Complexity task level C_t	O_c
	*adM$_{61}$	Manual Assembly/Disassembly	8	1.5	12
	*adM$_{71}$	Manual Assembly/Disassembly	2	1.5	3
	daM$_{81}$	Manual Assembly/Disassembly	4	1.25	5
$PV_3 - PV_4$	dM$_{13}$	Manual Disassembly	5	1.75	8.75
	*aM$_{14}$	Manual Assembly	5	1.75	8.75
	adM$_{21}$	Manual Assembly/Disassembly	2	1.75	3.5
	adM$_{22}$	Manual Assembly/Disassembly	2	1.75	3.5
	dM$_{33}$	Manual Disassembly	4	1.75	7
	aM$_{34}$	Manual Assembly	4	2	8
	dM$_{43}$	Manual Disassembly	1	1.75	1.75
	aM$_{44}$	Manual Assembly	1	2	2
	aM$_{51}$	Manual Assembly	1	1.75	1.75
	*adM$_{61}$	Manual Assembly/Disassembly	8	1.5	12
	*adM$_{71}$	Manual Assembly/Disassembly	2	1.5	3
	adM$_{81}$	Manual Assembly/Disassembly	4	1.25	5
		Overall Assembly/Disassembly complexity Index C_{TM}			232

Annex Table 10. Assembly/Disassembly Complexity Index C_{TM} for Alternative 2

Product Variant Reconfiguration	Module relationship	Operation	Number of operations T	Complexity task level C_t	O_c
$PV_0 - PV_1$	aM$_{11}$	Manual Assembly	5	1.75	8.75
	aM$_{21}$	Manual Assembly	2	1.75	1.75
	aM$_{22}$	Manual Assembly	1	1.75	1.75
	aM$_{31}$	Manual Assembly	4	2	8
	aM$_{41}$	Manual Assembly	1	2	2
	aM$_{51}$	Manual Assembly	1	1.75	1.75
	aM$_{61}$	Manual Assembly	5	1.5	7.5
	aM$_{71}$	Manual Assembly	2	1.5	3
	aM$_{81}$	Manual Assembly	2	1.25	2.5
$PV_1 - PV_2$	dM$_{11}$	Manual Disassembly	5	1.75	8.75
	*aM$_{12}$	Manual Assembly	5	1.75	8.75
	dM$_{21}$	Manual Assembly/Disassembly	2	1.75	3.5
	adM$_{22}$	Manual Assembly/Disassembly	3	1.75	3.5
	aM$_{23}$	Manual Assembly	1	1.75	1.75
	dM$_{31}$	Manual Disassembly	4	1.75	7
	aM$_{32}$	Manual Assembly	4	2	8
	dM$_{41}$	Manual Disassembly	1	1.75	1.75
	aM$_{42}$	Manual Assembly	1	2	2
	aM$_{51}$	Manual Assembly	1	1.75	1.75
	*adM$_{61}$	Manual Assembly/Disassembly	8	1.5	12
	*adM$_{71}$	Manual Assembly/Disassembly	2	1.5	3
	daM$_{81}$	Manual Assembly/Disassembly	4	1.25	5
$PV_2 - PV_3$	dM$_{12}$	Manual Disassembly	5	1.75	8.75
	*aM$_{13}$	Manual Assembly	5	1.75	8.75
	dM$_{22}$	Manual Assembly/Disassembly	2	1.75	3.5
	adM$_{23}$	Manual Assembly/Disassembly	3	1.75	3.5
	aM$_{24}$	Manual Assembly	1	1.75	1.75
	dM$_{32}$	Manual Disassembly	4	1.75	7
	aM$_{33}$	Manual Assembly	4	2	8
	dM$_{42}$	Manual Disassembly	1	1.75	1.75
	aM$_{43}$	Manual Assembly	1	2	2
	aM$_{51}$	Manual Assembly	1	1.75	1.75
	*adM$_{61}$	Manual Assembly/Disassembly	8	1.5	12
	*adM$_{71}$	Manual Assembly/Disassembly	2	1.5	3
	daM$_{81}$	Manual Assembly/Disassembly	4	1.25	5
$PV_3 - PV_4$	dM$_{13}$	Manual Disassembly	5	1.75	8.75
	*aM$_{14}$	Manual Assembly	5	1.75	8.75
	dM$_{23}$	Manual Assembly/Disassembly	2	1.75	3.5
	adM$_{24}$	Manual Assembly/Disassembly	3	1.75	3.5
	aM$_{25}$	Manual Assembly	1	1.75	1.75
	dM$_{33}$	Manual Disassembly	4	1.75	7
	aM$_{34}$	Manual Assembly	4	2	8
	dM$_{43}$	Manual Disassembly	1	1.75	1.75
	aM$_{44}$	Manual Assembly	1	2	2
	aM$_{51}$	Manual Assembly	1	1.75	1.75

Product Variant Reconfiguration	Module relationship	Operation	Number of operations T	Complexity task level C_t	O_c
	*adM_{61}	Manual Assembly/Disassembly	8	1.5	12
	*adM_{71}	Manual Assembly/Disassembly	2	1.5	3
	adM_{81}	Manual Assembly/Disassembly	4	1.25	5
		Overall Assembly/Disassembly complexity Index C_{TM}			244.3

Calculation of Pugh Complexity Index

$$CI = \sqrt[3]{N_c N_p N_i}$$

Annex Table 11. Pugh Complexity Index for Original Design and Alternatives 1 and 2.

	Original Design	**Alternative 1**	**Alternative 2**
Number of Components N_C	7	9	12
Number of Pieces N_p	16	19	21
Number of surfaces in contact N_i	21	24	26
CI	13.3	16.01	18.7

ANNEX VII: Material Selection calculations - Durability

Environmental Durability

Annex Table 12. Environmental Durability Calculation for manufacturing Scenarios

Material	Water Resistance	Acids Resistance	Organic Solvents	Chemical Resistance	UV Radiation Resistance	D_{env}	Overall Level
ABS	4	2	1	2	1	10	3
ABS/PC	3	2	1	2	2	10	3
PLA	3	1	2	2	3	11	4
PA11	4	1	3	2	2	12	4
PA12	4	1	3	2	2	12	4

Mechanical Durability

Annex Table 13. Calculated values of Mechanical Durability for manufacturing scenarios

	ABS	ABS/PC	PLA	PA11	PA12
Mechanical Durability	25.3	28.8	29.4	30.2	25.3

ANNEX VIII: Calculated Values for Comparative Radial Charts. Absolute and relative values for Manufacturing Scenarios.

Properties for Manufacturing Scenarios

Annex Table 14. Values for CO2 Footprint and Energy Consumption based on the kg of material

Values per kg of material (Lifecycle)	ABS	ABS/PC	PLA	PA11	PA12
CO2 footprint kg CO_2/ kg	5.6	14	5.3	5.8	10.7
Energy Consumption MJ/kg	133.7	214.5	75.1	302.2	201.8

Manufacturing Time

Original Design		Open Architecture Design	
Component	**Manufacturing Time (h)**	**Component**	**Manufacturing Time (h)**
Fingers + Thumb	41.6	Fingers + Thumb	17.8
Palms	15.64	Palms	17.96
Gauntlets	29.81	Gauntlets	13.6
Finger Pins	3.2	Finger Pins	2.8
Wrist Pins + Wrist Rings	0.63	Wrist Pins + Wrist Rings	0.88
-	-	Thumb Adaptors	5.5
TOTAL TIME	92.96	TOTAL TIME	58.5
TOTAL TIME PRODUCT FAMILY	**185.92**	**TOTAL TIME PRODUCT FAMILY**	**111.92**

Mass of open architecture product family

Annex Table 15. Detailed Mass Calculation for open architecture prosthetic hand

	Part	Mass	Qty	Total	Total Prosthesis
100%	Palm	38.12	1	38.12	103.69
	Gauntlet (two parts)	26.36	1	26.36	
	Finger	5.87	4	23.48	
	Thumb	4.67	1	4.67	
	Finger Pin	0.36	5	1.8	
	Wrist Pin	0.41	2	0.82	
	Wrist Ring	0.48	2	0.96	
	Thumb Attachment	7.48	1	7.48	
	Part	Mass	Qty		
110%	Palm	49.31	1	49.31	93.46
	Gauntlet	26.36	0	0	
	Finger	7.65	4	30.6	
	Thumb	6.07	1	6.07	
	Finger Pin	0.36	0	0	
	Wrist Pin	0.41	0	0	
	Wrist Ring	0.48	0	0	
	Thumb Attachment	7.48	1	7.48	
	Part	Mass	Qty		

	Part	Mass	Qty	Total	Total Prosthesis
120%	Palm	63.2	1	63.2	120.9
	Gauntlet	26.36	0	0	
	Finger	10.64	4	42.56	
	Thumb	7.66	1	7.66	
	Finger Pin	0.36	0	0	
	Wrist Pin	0.41	0	0	
	Wrist Ring	0.48	0	0	
	Thumb Attachment	7.48	1	7.48	
	Part	Mass	Qty		
130%	Palm	77.77	1	77.77	142.73
	Gauntlet	26.36	0	0	
	Finger	12.01	4	48.04	
	Thumb	9.44	1	9.44	
	Finger Pin	0.36	0	0	
	Wrist Pin	0.41	0	0	
	Wrist Ring	0.48	0	0	
	Thumb Attachment	7.48	1	7.48	
TOTAL PRODUCT FAMILY (Left and Right hand)					921.56

Manufacturing Time

Annex Table 16. Detailed Manufacturing Time Calculation for Prosthetic Hand Family (Case Study)

Manufacturing Cluster (Additive FDM)	Manufacturing time (h)	Total (h) PV_1–PV_4
Palms	17.96	55.96 (106.08 for the whole product family)
Gauntlets (x2 parts)	13.6	
Fingers + Thumbs	17.8	
Thumb Adapter	5.53	
Finger Pin, Wrist Pins and Wrist Rings	1.07	

Cost

The manufacturing cost was calculated using the same values employed in the diagnosis of Chapter 5.

m: According to values listed in Annex Table 17.

Annex Table 17. Mass consumption for all manufacturing scenarios

	PLA	PA11	PA12	PLA+PA11	PA12+PLA
Mass Consumption - kg	1.12	0.94	0.93	1.08	0.93
Material Cost - USD	2.4	15.4	7.76	-	-

C_m: According to values listed in Annex Table 17. (Material cost – USD)

T: 111.92 hours (eight product variants – all product family)

C_c: 20000 USD

t_{wo}: 17520 hours

C_{oh}: 5 USD per hour

Health Risk Exposure

Calculated according to Annex I.

Overall Results

Annex Table 18. Absolute values for Manufacturing Scenarios

	PLA Original Design	PLA	PA11	PA12	PLA+PA11	PA12+PLA
Mass Consumption kg	1.87	0.92	0.77	0.76	0.91	0.77
CO_2 footprint kg CO_2	9.91	4.88	4.47	8.13	4.85	7.92
Energy Consumption MJ	140.44	69.17	233.00	153.37	4.85	147.78
Cost - USD	1119.79	720.77	730.44	724.46	721.40	724.22
Health Risk Exposure	4.00	4.00	3.00	4.00	3.50	4.00

Annex Table 19. Relative values for Manufacturing Scenarios

	PLA Original Design	PLA	PA11	PA12	PLA+PA11	PA12+PLA
Mass Consumption	1.00	0.49	0.41	0.41	0.49	0.41
CO_2 footprint	1.00	0.49	0.45	0.82	0.49	0.80
Energy Consumption	1.00	0.49	1.66	1.09	0.03	1.05
Cost	1.00	0.64	0.65	0.65	0.64	0.65
Health Risk Exposure	1.00	1.00	0.75	1.00	0.88	1.00

ANNEX IX: Detailed description of values for calculation parameters – OAP family

Annex Table 20. Description of values showed in Table 28, Chapter 5.

Calculation Parameter	Origin
Total mass of the product family - Mt	Total mass of the product family measured in kg. Values were obtained from Annex Table 5 and Annex Table 15.
Total mass of reusable components - Mr	Correspond to the mass of Gauntlet, Finger Pins, Wrist Pins and Wrist Rings.
Recycling Efficiency - Ei	90% is assumed for the PLA case study
Fraction of recyclable mass for component i - Fi	100% of the mass of the product family is recyclable. Therefore fraction is equal to one (1).
Mass of virgin feedstock in the PF - V	10% is assumed for the PLA case study
Mass of unrecoverable waste in PF manuf. – Wu	Unrecoverable waste is considered zero
Mass of unrecoverable waste generated to produce recycled feedstock - Wf	10% is assumed for the PLA case study
Mass of unrecoverable waste generated during recycling - Wr	10% is assumed for the PLA case study
Number of product variants - P	Eight product variants (PV_1 to PV_8)
Number of reconfigurations in the product family -R	Six reconfigurations are possible. Three for each gauntlet during changes from PV_1 to PV_4 and from PV_5 to PV_8.
Number of pieces in the PF – n	128 for the original design and 78 for the open architecture design
Component Variety within the product Family C_v	25 varieties (See Table Annex Table 21)

Annex Table 21. Functional Range and Functional Variety Calculation

Component	Variety	number of configurations in which the component can offer more than one function	Capable of working in an operational range
Palm	4	2	No
Finger	4	1	No
Thumb	4	1	No
Thumb Adapter Right	4	1	No
Thumb Adapter Left	4	1	No
Finger Pin	1	1	Yes
Gauntlet Right Part	1	1	Yes
Gauntlet Left Part	1	1	Yes
Wrist Pin	1	1	Yes
Wrist Ring	1	1	Yes
TOTAL COMPONENT VARIETY C_v	**25**		

Number of component variety capable of working in an operational range C_1:

according to Annex Table 21 , five variety of components are remarked with “yes” in the table. Therefore, the value for the parameter is 5 (five).

Number of component variety with more than one functionality C_2:

According to Annex Table 21, the palm offer 4 variety of pieces that offer more than one function. Therefore, the value for this parameter is 4 (four).